

A GENERATIVE PROCESS PLANNING SYSTEM FOR MILLING OPERATIONS

By

PRAFULLA K. AHERRAO

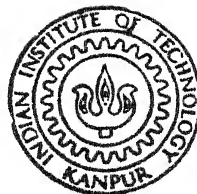
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DEPARTMENT OF MECHANICAL ENGINEERING
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A GENERATIVE PROCESS PLANNING SYSTEM FOR MILLING OPERATIONS

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By
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to the
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DEDICATED
TO
MY PARENTS

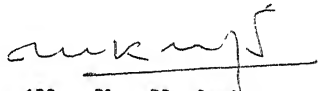
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CERTIFICATE

This is to certify that the present work on A Generative Process Planning System for Milling Operations, by Prafulla K. Aherrao has been carried out under our supervision and has not been submitted elsewhere for the award of a degree.

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NOMENCLATURE

a_p	=	approach of cutter to workpiece, mm
A_i	=	instantaneous area of chip; mm^2
A_{S_i}	=	instantaneous area of shear; mm^2
B	=	BHN
C	=	Cost per piece, Rs./piece
C_p	=	purchase cost of the cutter; Rs./cutter
C_w	=	cost of the grinding wheel to sharpen the cutter, Rs./cutter
C_c	=	cost of each insert; Rs./insert
C_{obj}	=	objective function
C_e	=	face clearance angle, deg.
C_o	=	corner angle, deg.
D	=	diameter of the cutter, mm
d	=	depth of cut/slot, mm
e	=	overtravel of milling cutter past workpiece, mm
f	=	feed rate; mm/rev
f_t	=	feed rate per tooth; mm/tooth
F_{S_i}	=	instantaneous shear force kg_f/mm^2
F_{T_i}	=	instantaneous tangential force, Kg_f/mm^2
G	=	grinding cost (labour + overhead); Rs./min
k_1	=	number of times the cutter can be resharpened before being discarded
k_2	=	number of times the insert can be used before being discarded

K_{Sp}	=	specific cutting energy, HP/mm ³ /min
k	=	tool life constant
L	=	length of the work surface; mm
l_c	=	length of uncut chip; mm
M	=	milling cost (labour + overhead), Rs./min
N_L	=	batch size or lot size
n, n_1	=	exponents of tool life equation
P	=	production rate, pieces per hour
P_c	=	total power consumed at any instant in cutting, in hp
P_{cT}	=	total maximum power consumed during cutting, in hp
P_{max}	=	maximum available power in hp
P_i	=	instantaneous power in hp
R	=	Radius of cutter, mm
r	=	rapid traverse rate; mm/min
t_o	=	time to set up machine tool for operation, min
T_{mm}	=	tool life, mm/edge
t_c	=	tool changing time, min
t_s	=	time to resharpen the cutter, min.
t	=	instantaneous chip thickness
t_{max}	=	maximum chip thickness, mm
U	=	total energy consumed/time, hp
U_i	=	instantaneous energy consumption/time, hp
V	=	cutting velocity, m/min
$\check{v}(\lambda)$	=	dual function
W	=	width of cut, mm
Z	=	number of teeth in cutter

α_n	=	normal rake angle in deg
β_n	=	normal rake angle in deg
ϕ_n	=	normal shear angle in deg
ϕ	=	instantaneous position of any part of cutting edge in cutting, measured from the vertical axis, deg.
ϕ_1	=	the angle at which the cutting starts, measured from the vertical axis, deg
ϕ_2	=	the angle at which the cutting ends, measured from the vertical axis, deg.
β	=	friction angle, deg
η_c	=	chip flow angle, deg
λ	=	helix angle, deg
α	=	angle through which the leading point of the cutting edge moves from the beginning of the cutting action, deg
δ	=	engagement angle, deg
α_E	=	effective rake angle, deg
τ_s	=	dynamic shear stress, kg_f/mm^2
σ_u	=	ultimate tensile strength kg_f/mm^2
Δ	=	percentage elongation of work material
ψ_i	=	instantaneous position of the cutting edge in cutting, measured from the vertical axis.
ψ_i'	=	instantaneous entry angle of the cutting edge in cutting, measured from the vertical axis
ψ_i''	=	instantaneous exit angle of the cutting edge in cutting, measured from the vertical axis

ABSTRACT

In the present work, a computerized process planning system, for parts requiring milling operations, is designed, developed and implemented. This interactive system uses generative approach of process planning. The system is capable of handling the three major milling operations viz. end milling, face milling and peripheral milling.

The geometric programming technique is used for determining the machining parameters. Emphasis is given on the constraining equations used in the optimization model. The power equations are derived from the metal cutting analysis. The cutter selection is automatic to some extent.

The system gives detailed process plan giving sequence of operations, optimal machining parameters for each operation, cost per piece and the production rate.

The system is implemented on IBM compatible PC-XT/AT. The programs are written in Turbo PASCAL and dBase III plus is used as database management system.

CHAPTER I

INTRODUCTION

The markets for mass produced consumer goods (e.g. cars and fans) as well as capital goods (e.g., machine tools) tend to demand increased level of sophistication due to the increasing level of competition. For capturing such a market, the industries have been constantly making improvements in their products and are trying to make the products available at relatively lower cost. Thus, production, which is the primary function of a manufacturing industry, is getting more and more attention along with the other organizational activities like marketing, sales, etc..

To remain competitive, lead time must be reduced in order to cope up quickly and efficiently with the alterations and additions in the present trend. For this reason, various functions such as design, planning, manufacturing, scheduling, assembly, etc. should be speeded up. Computer has played a very significant role in speeding up these functions.

With the use of computers in design and manufacturing, the productivity and overall efficiency of the manufacturing systems has improved considerably. Computer Aided Design (CAD) has however, not been integrated fully with Computer Aided Manufacturing (CAM) yet, as regards the flow of engineering information [1]. Process planning, which interfaces design and

manufacturing, is extremely important towards integrating CAD and CAM and thus implementing Computer Integrated Manufacturing Systems (CIMS).

1.1 PROCESS PLANNING

Process Planning is the act of preparing detailed work instructions from the design data to produce a part. It bridges Design and Manufacturing functions.

"Process Planning" is the function within a manufacturing activity that establishes the machining processes and parameters, as well as the machine tools to be used to convert a part from its initial form to a final form predetermined from its engineering drawing [2].

The process plan is frequently called as route sheet, or operation sheet, or operation planning summary. The detailed plan contains the route, processes, process or machining parameters, machine tools and cutting tools for each operation. Cost and production rate is also, usually, given in the process plan.

There are numerous factors that affect process planning; the shape, tolerance, surface finish, size, material type and the manufacturing system itself. All contributes to the selection of operations and the operation sequence.

1.1.1 Traditional Process Planning

Usually, the process planning is carried out by an experienced person using his past experience in shop floor. Thus,

the experience and judgement of the process planner play crucial role in process planning. However, individual engineers have their own views about what constitutes the best sequence. Hence, differences in the process plans developed by different planners is obvious.

A process planner, after examining a new part, decides the operations to be performed, and their sequence. For machining conditions, the process planners usually refers to metal cutting handbooks, manufacturers' catalogues and nomograms.

1.1.2 Automated Process Planning

In simple words, use of computers for process planning is automated process planning.

In an automated process planning system, the logic, judgement and experience required are incorporated into computer programs. Based on the features of the given component, the program automatically gives the process plan(s). As a result of this, the process plans obtained are more rational and consistent.

The methods in automated process planning classically involve two approaches: (i) Variant Process Planning and (ii) Generative Process Planning.

The variant approach can be defined as the preparation of process plan through the manipulation of a standard plan. The parts manufactured by the firm, are grouped into part families on the basis of their design and manufacturing characteristics. The

composite part concept is used for generating standard plans for each family. The process plan for a new part is prepared by editing the standard plan of the part family to which it belongs.

The generative approach is the logical creation of a process plan, using computers from scratch, automatically and without any human intervention. Input to the system includes a comprehensive description of the workpart. This approach is different than the variant process planning approach in the sense that it does not involve the retrieval of any process plan.

In practice, generative process planning systems are far from universal in their applicability. They tend to fall short of a truly generative capability.

Process Planning, whether manual or automated can be divided into five phases [4]:

1. Selection of processes and tools,
2. Sequencing the operations
3. Identification of all non-machining elements and estimating the non-machining items,
4. Selection of work piece holding devices,
5. Determination of the proper cutting conditions and cutting times to machine the workpiece to specified dimensions.

1.2 LITERATURE SURVEY

1.2.1 An Overview

As discussed earlier, a process planner carries out various tasks in planning. Some are numerical tasks, e.g. calculation of machining parameters, some are logical, e.g. rough machining should be done prior to finish machining while some are the library reference tasks, e.g., availability of cutting tools and machine tools. But, most of the tasks require expert knowledge and experience, e.g. deciding the sequence of operations, selection of tools etc. It is the complexity of this type of decision making, which is a barrier to a generalized automate process planning.

Despite this, lot of efforts is being put to automate the process planning function. The Scientific and Technical Committee "Optimization" (STC O") of CIRP in 1982, surveyed the Computer - Aided Process Planning Systems [3]. The survey was intended to give a comprehensive picture of the actual knowledge in the field of Computer-Aided Process Planning Systems, and to attract the attention of the researchers and the research bodies towards process planning.

If we go through the steps involved in process planning as listed in the previous section, the first important function is the selection of processes. Attempts have been made to extract manufacturing-specific knowledge about the part from the CAD-generated objects. Henderson, et.al. [5] have proposed an

approach to automatically extract feature from a CAD - database. It performs well for certain class of objects containing swept features. Jee & Fu [6] have used one of the solid modeling technique - Constructive Solid geometry (CSG) for extraction and unification of feature representations. The technique is based on the notion of principal axis and it is quite useful for primitives which can be characterized by a single axis like cylinder, cone and sphere as well. Wang and Wysk [7] have used a wire frame based CAD database to extract surface features in the proposed Turbo-CAPP system.

R. Weill, et.al. [3] have proposed a method of sequencing the operations by solving a precedence matrix of operations. The user has to enter all the information required for the precedence matrix. This involves maximum interaction with the user, and computer aids only the computational work involved in it.

Second important function of process planning is determination of machining parameters. Machinability data systems are intended to select cutting speed and feed rate given the following characteristics of the operation [8].

1. Type of machining operation
2. Machine tool
3. Cutting tool
4. Workpart
5. Operating parameters other than feed and speed

Experience and judgement of process planners, and machining data handbooks have been traditionally used. In Automated process planning systems, computerized machinability data systems are being used.

Computerized machinability data systems have been classified into:

1. Database Systems
2. Mathematical Model Systems

Database systems are the collection of large quantities of data stored from laboratory experiments and shop experience. Mathematical model systems determines the optimum cutting conditions for an operation. Most of the work in determining machining parameters has been done in mathematical model systems.

Ermer [9] determined the optimum cutting conditions of a constrained machining problem for a single operation by applying geometric programming. Hati and Rao [10] found the optimum feed and speed by treating the objective function and the constraints as probabilistic. Rao and Hati [11] used non-linear programming technique to determine the machining parameters for a job requiring multiple operations. Malakooti and Deviprasad [12] presented a decision support system using multiple criterion decision making approach. They considered that there are several conflicting objectives, and obtained the best compromising solution.

1.2.2 Survey of CAPP Systems

In the survey by STC.0" of CIRP in 1982, some 55 CAPP systems were reported to be functioning. The number must have increased by now. Both the approaches of automated process planning - variant and generative - have been reported to be used. However, most of the existing process planning systems are variant systems.

ICAPP (An Interactive Process Planning System for Prismatic Parts) [4] is an interactive process planning system for non-rotational prismatic parts developed at Department of Mechanical Engineering, UMIST. The ICAPP logic is a combination of the variant approach and the generative approach. Variant planning via the part family concept is applied by planning a composite part for each family and standard plans developed are stored in a file. The parts in the family are processed according to this data.

TOJICAP (A System of Computer-Aided Process Planning System for Rotational Parts) [13] is developed in Department of Mechanical Engineering, Tongji University, Shanghai, China. It is an interactive process planning system for rotational parts. The logic used is the combination of the variant approach and the generative approach. The standard process sequence is retrieved from the standard plans of the composite parts but the machining parameters are generated automatically. The part description is entered interactively by the user.

APPAS (Automatic Process Selection and Planning Program) [14] is a generative process planning system developed at Purdue

University for planning of processes done on machining centers and N.C. Drills. APPAS uses decision tree type logic, and the machining surfaces for which planning is done include holes, slots and planes, flat and convex. COFORM coding structure has been used to input surface information. The system has the additional capability to determine the machining requirements like horsepower and machine time.

STOPP (Sequential and Tool Oriented Process Planning) [14] is a generative process planning system developed at Purdue University for machining centers. The process plans are designed to utilize the available tools and hence the name 'tool oriented process planning. Pattern recognition technique is used to recognize the exact shape of the elementary machined surfaces. Among other CAPP systems, MITURN, COMCAPP, MIPLAN are variant systems while GENPLAN, AUTAP, CPPP are the generative systems. AUTAP is considered to be one of the most complete process planning systems in use. The parts planned by AUTAP consist of rotational and sheet metal parts.

1.3 SCOPE OF THE THESIS

From the above discussions, it can be seen that the field of automated process planning is wide open for research. In the present work, emphasis has been given to the constraining equations used in the optimization model for determining the machining parameters. An attempt has been made to use power equations derived from the metal cutting analysis. A mathematical analysis for finding the power equation is given, for the three

CHAPTER 2

SYSTEM ANALYSIS AND DESIGN

This chapter presents description, analysis and design of the proposed system. System description is presented in Sec. 2.1, System Analysis in Sec. 2.2, and Database Description in Sec. 2.3.

2.1 SYSTEM DESCRIPTION

A generative approach has been used for process planning involving three major milling operations viz. Peripheral milling, face milling and end milling. The system considered for analysis and design consists of machining centers as well as conventional milling machines. It has been assumed that the vertical milling machines and the vertical machining centers are capable of performing face milling and end milling operations, while horizontal milling machines and horizontal machining centers are capable of performing only peripheral milling. The system also includes a set of assorted cutters capable of performing milling operations. The details of the cutters and the machine tools have been discussed later in this chapter.

Following assumptions have been made in order to further characterize the various aspects of the system.

1. All the cutters and machine tools are available for the process planning of each part.

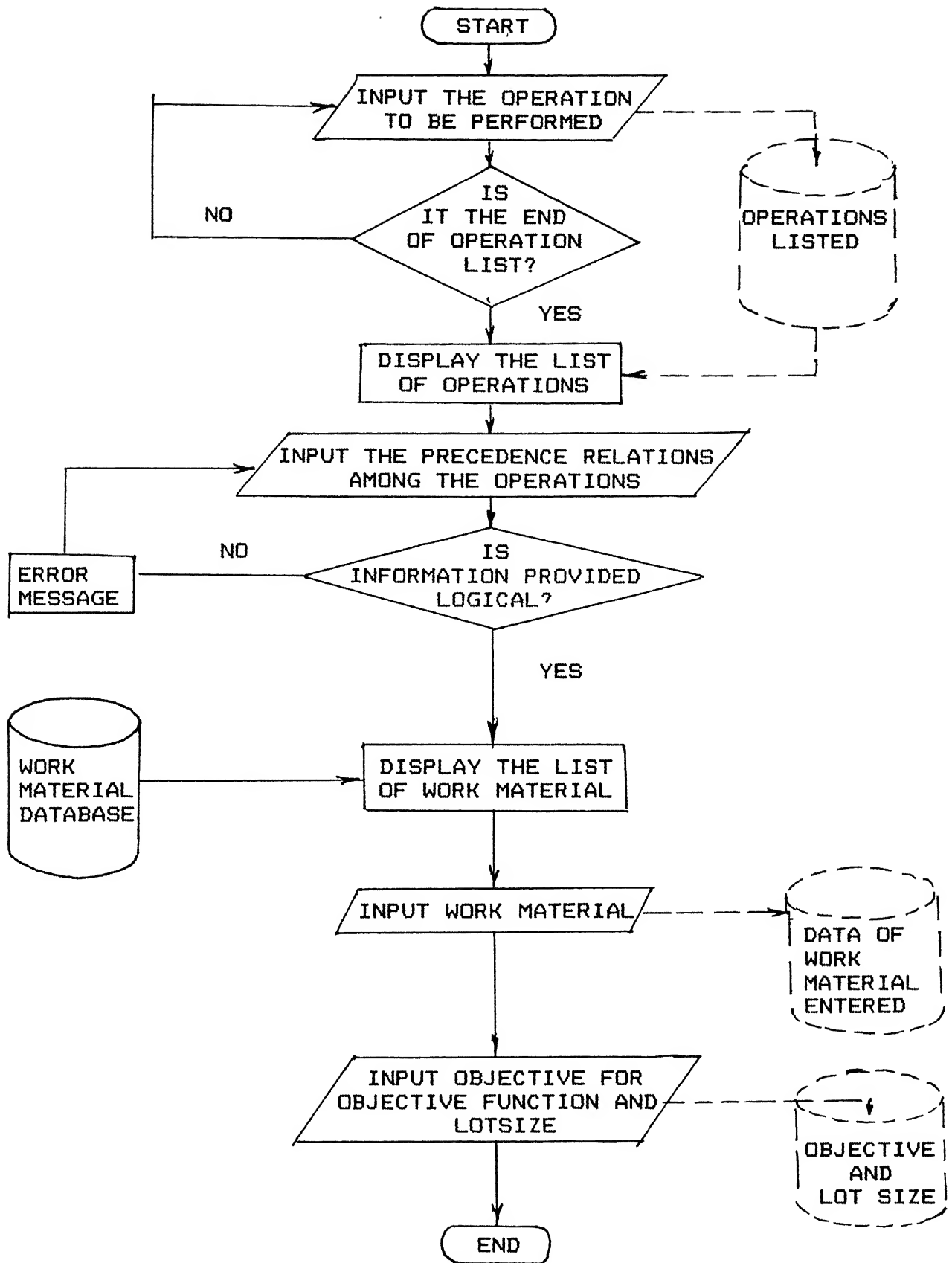
2. Suitable jigs and fixtures are available to handle all the workpieces.
3. The Taylor's tool life equation is considered to be valid for describing the life of milling cutters.
4. At a time, only one cutter is used, i.e. there is no provision of gang milling.
5. Machining centers/CNC machines have infinitely variable speed drives.

2.2 SYSTEM ANALYSIS

The system, in general, consists of input, processing, and output modules. We shall discuss these modules in the following paragraphs.

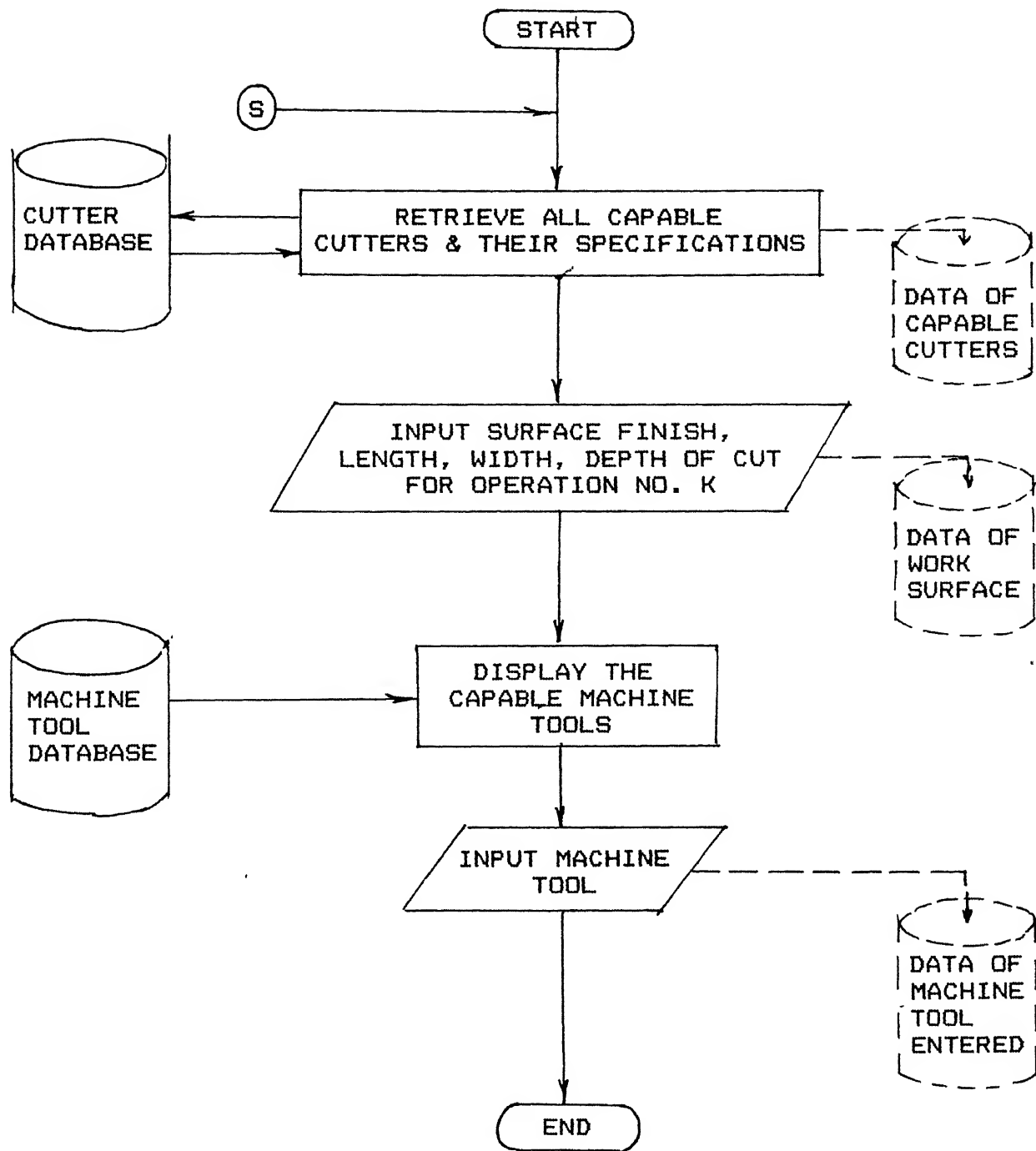
In designing the input modules, the nature of input data should be studied to classify them in distinct groups to facilitate data entry. The input module receives the inputs from the user in two distinct phases. In the first phase i.e phase I (Fig. 1) are received, all the data which are to be entered once for a part, e.g. the operations to be performed, precedence relation among the operations listed, the work material, the objective function for optimization, and the batch size. In the second phase (Fig. 2), the data which are entered are with respect to each operation. This phase is thus, repeated for each of the listed operations.

After listing all the operations which are to be performed, and based on the precedence relations given by the user it is



DATA BASES SHOWN DOTTED ARE TEMPORARY DATABASES

Fig. 1: Input module - Phase I.

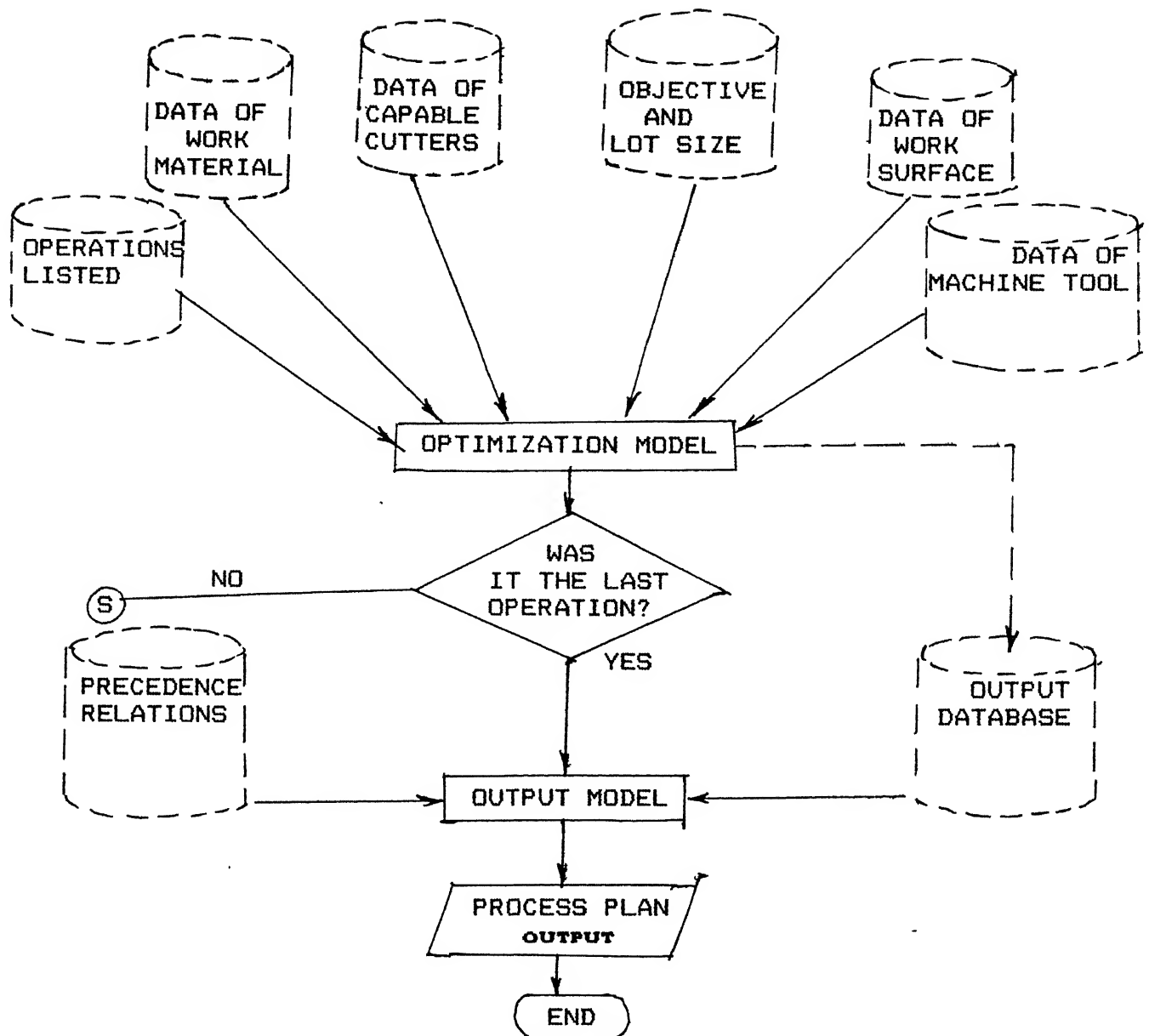


DATABASES SHOWN DOTTED ARE TEMPORARY DATABASES.

Fig. 2: Input module - Phase II.

checked whether the data provided is logical or not. If the data provided is not logical, then, the user is given the message that the data provided is illogical and is asked to enter the precedence relations among the various listed operations again. On the basis of the work material entered by the user, all the data regarding that work material are stored in one temporary file. The objective function for optimization and the lot size entered are stored in another temporary file (Fig. 1).

Depending upon the first operation to be performed and the hardness of the work material, all the cutters capable of performing that operation and of tool material which can be used for that work material are retrieved and stored in one temporary file. For example, if the operation to be performed is end milling and the hardness of the work material is 260 BHN, then all the end mills of carbide tool material are stored in the temporary file. Some of the cutters in this temporary file are further discarded using some rules which have been discussed in Sec. 2.2.1 machine tools capable of performing the operation under consideration are retrieved from the machine tool database and displayed on the screen for the user to select one of the machine tools. For example, if the operation to be performed is end milling then, the machine tools on which end milling can be performed are retrieved from machine tool database and are displayed on the screen. The data regarding the machine tool selected by the user is then, stored in another temporary file (Fig. 2).



DATABASES SHOWN DOTTED ARE TEMPORARY DATABASES.

Fig. 3: Flow chart of processing and output modules.

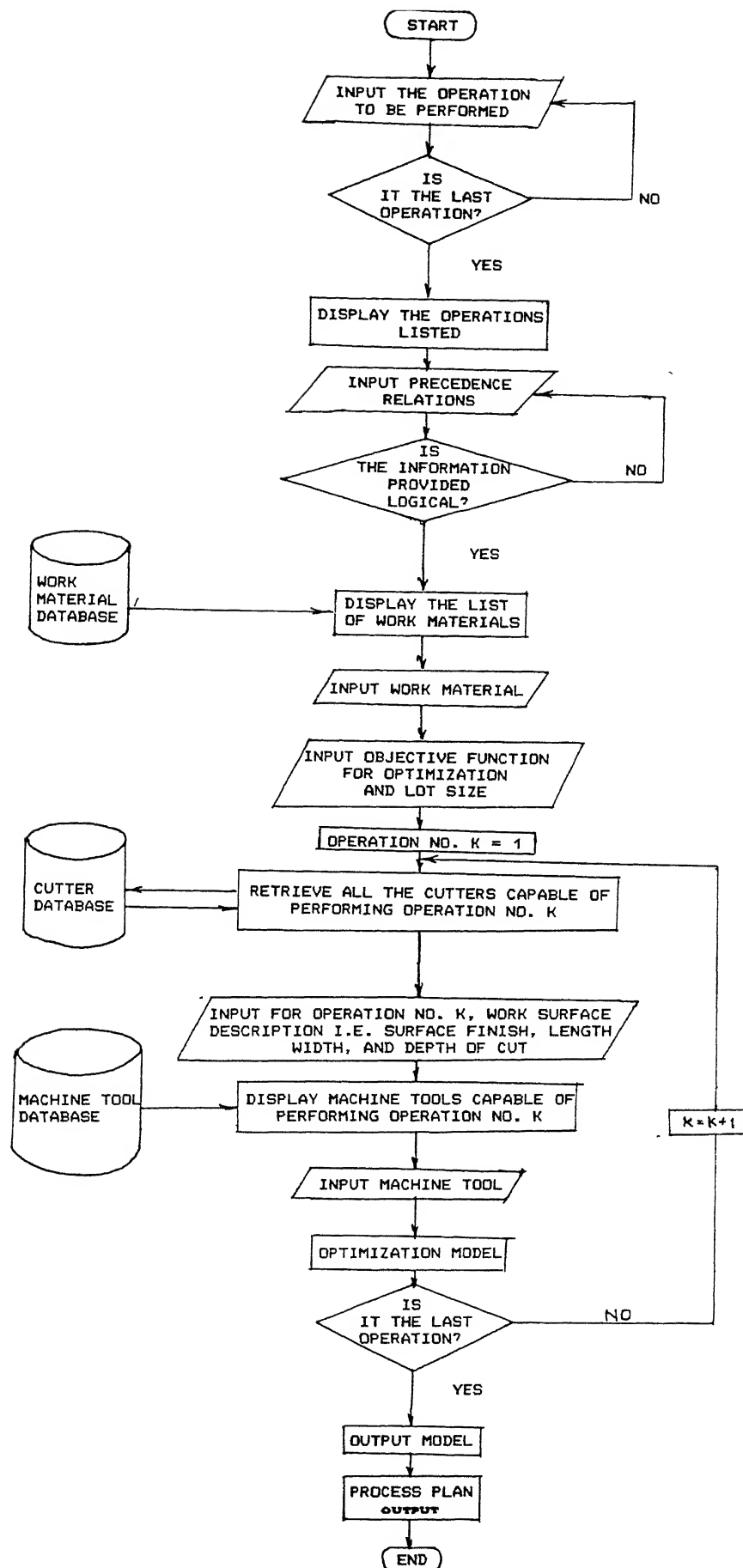


Fig. 2: System flow chart.

The data from all the temporary files is then read into the optimization model (Fig. 3), which determines the optimal machining parameters. The details of the optimization model are discussed in Sec. 2.2.2.

After obtaining the machining parameters for all the listed operations, depending upon the precedence relations entered by the user, the detailed process plan is given with sequence of operations to be performed, optimal machining parameters for each operation, various costs, and production rate.

The flow chart of the system is given in Fig. 4.

Now we shall describe the rules of selection of cutting tools and optimization model in the subsequent subsections.

2.2.1 Selection of Cutting Tools

In the present system, an attempt has been made for automatic selection of cutting tools. The selection procedure is as follows:

1. All the cutters capable of performing intended operation, are considered. For example, for end milling operation only end mills are considered.
2. If the workpiece hardness is greater than 250 BHN, then HSS cutters are discarded, only carbide cutters are considered. But, if the hardness is less than or equal to 250 BHN then both HSS and Carbide cutters are considered.

3. The strength of work material plays an important role in selecting the cutter. To take account of this aspect, the work materials are classified on the basis of their ultimate strength.

If the ultimate strength is:

- (i) less than or equal to $50 \text{ kg}_f/\text{mm}^2$, the work material is classified under category I.
- (ii) more than $50 \text{ kg}_f/\text{mm}^2$ but less than $100 \text{ kg}_f/\text{mm}^2$, the work material is classified under category II.
- (iii) more than or equal to $100 \text{ kg}_f/\text{mm}^2$, the work material is classified under category III.

The cutters are selected as follows:

(a) LIP ANGLE CRITERION

The lip angle of all the cutters under consideration are determined. Based on the lip angles of the available cutters, the selection can be done according to one of the following cases.

CASE I: If the lip angles of all the available cutters is same, then no cutter is discarded on the basis of lip angle.

CASE II: If the cutters with two different lip angles are available, then the cutters with higher lip angle are considered for Category III and lower lip angle cutters are considered for Categories I and II.

CASE III: If cutters with three different lip angles are available, then the cutters with highest lip angle for Category III, the cutters with lowest lip angle for

Category I, and the cutters with intermediate lip angle for Category II are considered.

CASE IV: If cutters with more than three different lip angles are available then:

All the cutters with higher three lip angles are considered for Category III.

All the cutters with lower three lip angles are considered for Category I.

And for Category II, all the cutters except those with highest and lowest lip angles are considered.

(b) HELIX ANGLE CRITERION

Considering the helix angles of the cutters available after the lip angle criterion:

CASE I: If the helix angle of all the cutters available is same, then no cutter is discarded.

CASE II: If the cutters with two different helix angles are available then the lower helix angle cutters are considered for Categories II and III and higher helix angle cutters are considered for Category I.

CASE III: If the cutters with more than two different helix angles are available then:

All the cutters with highest helix angle are considered for Category I.

All the cutters with lowest helix angle are considered for Category III.

And all the cutters except those with maximum and minimum helix angle are considered for Category II.

The helix angle criterion is not applicable to the side and face peripheral milling cutters as they have zero helix angle.

(c) RAKE ANGLE CRITERION

The criterion is applied only to the peripheral milling cutters. For down milling, cutters with highest rake angle are recommended to avoid interference of the chip in cutting action. And for up milling cutters with lowest rake angle are recommended.

4. In end mills, cutters with dia less than the width of slot to be cut are discarded.
5. Finally, if more than one cutter qualify, then the cutter which gives the optimum objective is recommended.

2.2.2 Determination of Optimal Machining Parameters

For finding the machining parameters, geometric programming method has been used, as it is effective when the constraints are non-linear and the objective function is of more than second degree. The model formulation is given here. For steps involved in optimization, see Appendix (A).

Model Formulation

(a) Objective Function for Optimization

Thus, Cost per piece is one of the objective functions considered in the model formulation of machining operations.

Other objective function considered is maximizing the production rate. If a machine tool becomes a "bottleneck" in a production sequence, it might be necessary to operate at the cutting conditions for maximum production rate. However, this is generally not the normal situation and cutting conditions are usually selected from the viewpoint of minimizing costs, under the assumption that operating at minimum cost will tend to increase profits.

For milling operation, cost per piece (Rs./piece) for solid cutters is given by [Field et.al. 1969] [15]

$$C = M \left(\frac{\pi D (e + L)}{1000 f V} + \frac{2a_p + e + L}{r} + \frac{t_o}{N_L} + \frac{L t_c}{Z T_{mm}} \right) + \frac{L}{Z T_{mm}} \left(\frac{C_p}{k_1 + 1} + Gts + C_w \right) \quad (2.1)$$

machining time
rapid traverse time
setup time
cutter change time

cutter depreciation cost
cutter resharpening cost
grinding wheel cost

and, cost per piece for throw away inserts is given by

$$C = M \left(\frac{\pi D (e + L)}{1000 f V} + \frac{2a_p + e + L}{r} + \frac{t_o}{N_L} + \frac{L t_c}{T_{mm}} \right) + \frac{L}{Z T_{mm}} \left(\frac{C_p}{k_1 + 1} + \frac{Z C_c}{k_2} \right) \quad (2.2)$$

machining time
rapid traverse time
set-up time
cutter change time

cutter body depreciation cost
throw away insert cost

Taking into account various time factors in milling, production rate in pieces per hour is given by

$$P = 60 / \left(\frac{\pi D (e + L)}{1000 f V} + \frac{2a_p + e + L}{r} + \frac{t_o}{N_L} + \frac{L t_c}{Z T_{mm}} \right) \quad (2.3)$$

Substituting Taylors tool-life equation

$$T_{mm} = k / (V^{1/n} f^{1/n_1}) \quad (2.4)$$

$$\text{or } T_{mm} = k / (V^b f^a) \quad (2.5)$$

where, $b = 1/n$, and $a = 1/n_1$.

$$C = \frac{M \pi D (e + L)}{1000 f V} + \frac{(2a_p + e + L) M}{r} + \frac{t_o M}{N_L} + \frac{L}{Z T_{mm}} (t_c M + \frac{C_p}{k_1 + 1} + G t_s + C_w);$$

or,

$$C = \frac{M \pi D (e + L)}{1000 f V} + \frac{(2a_p + e + L) M}{r} + \frac{t_o M}{N_L} + \frac{L f^a V^b}{Z k} (t_c M + \frac{C_p}{k_1 + 1} + G t_s + C_w); \quad (2.6)$$

for throw away inserts the equation would become

$$C = \frac{M \pi D (e + L)}{1000 f V} + \frac{(2a_p + e + L) M}{r} + \frac{t_o M}{N_L} + \frac{L f^a V^b}{Z k} (t_c M + \frac{C_p}{k_1 + 1} + \frac{Z C_c}{k_2}) \quad (2.7)$$

From equation (2.6), it is clear that second and third terms are not the functions of feed and velocity so we can exclude them for optimization purpose and we can take objective function as

$$C_{obj} = \frac{M \pi D (e + L)}{1000 f V} + \frac{L f^a v^b}{Z k} (t_c M + \frac{C_p}{k_1 + 1} + G t_s + C_w); \quad (2.8)$$

and in general form, we can take objective for as

$$C_{obj} = C_{01} f^{a_0} v^{b_0} + C_{02} f^{oc} v^{od}; \quad (2.9)$$

For solid H.S.S. cutters,

$$C_{01} = \frac{M \pi D (e + L)}{1000}; \quad a_0 = -1, \quad b_0 = -1$$

$$C_{02} = \frac{L}{Z k} (t_c M + \frac{C_p}{k_1 + 1} + G t_s + C_w); \quad oc = a, \quad od = b$$

Similarly for throw away inserts, the objective function can be taken as

$$C_{obj} = \frac{M \pi D (e + L)}{1000 f V} + \frac{L f^a v^b}{Z k} (t_c M + \frac{C_p}{k_1 + 1} + \frac{Z C_c}{k_2}) \quad (2.10)$$

So the constants in generalized form i.e. (2.9), in this case will be

$$C_{01} = \frac{M \pi D (e + L)}{1000}; \quad a_0 = -1, \quad b_0 = -1$$

$$C_{02} = \frac{L}{Z k} (t_c M + \frac{C_p}{k_1 + 1} + \frac{Z C_c}{k_2}); \quad oc = a, \quad od = b$$

If we look into the equation (2.3) for production rate

$$P = 60 / \left(\frac{\pi D (e + L)}{1000 f V} + \frac{2a_p + e + L}{r} + \frac{t_o}{N_L} + \frac{L t_c}{Z T_{mm}} \right) \quad (2.11)$$

In order to maximize the production rate, the expression in the denominator of the RHS in eqn. (2.11) should be minimized i.e. our objective function can be

$$C_{obj} = \frac{\pi D (e + L)}{1000 f V} + \frac{L t_c V^b f^a}{Z k} \quad (2.12)$$

again the second and third terms have been excluded as they are not the functions of feed and velocity. So constants in the generalized form (2.9) in this case will be

$$C_{01} = \frac{M \pi D (e + L)}{1000} ; a_0 = -1, b_0 = -1$$

$$C_{02} = \frac{L t_c}{Z k} ; c_0 = a, d_0 = b;$$

Thus, for our optimization model, we are using generalized form (2.9) as the objective function.

(b) Formulation of Constraints

To achieve the advantageous value of the machining parameters, these have to be decided in relation with several practical constraints of the process. The logic governing the formulation of the constraints has been discussed here.

1. Surface Finish

In peripheral milling, the surface finish obtained, using a cutter of diameter D , at feed rate f and having Z number of teeth is given by [16].

Peak to valley height

$$h = \frac{f^2}{Z^2 \cdot 4D} \quad (2.13-a)$$

If h_{\max} is the max permissible value of peak to valley height, then,

$$h \leq h_{\max}$$

or

$$\frac{h}{h_{\max}} \leq 1$$

or

$$\frac{f^2}{4DZ^2 h_{\max}} \leq 1$$

or

$$C_{11} \cdot f^2 \leq 1 \quad (2.13)$$

where

$$C_{11} = \frac{1}{4DZ^2 h_{\max}}$$

As it is clear from the generalized equation (2.9) for objective function, that, we are taking feed ' f ' and cutting velocity ' V ' as the design variables in our mathematical model for optimization. Thus, we can write equation (2.13) in generalized form having both the design variables as

$$C_{11} f^{a_1} V^{b_1} \leq 1 \quad (2.14)$$

where

$$a_1 = 2$$

$$b_1 = 0 \text{ and}$$

$$C_{11} = \frac{1}{4DZ^2 h_{max}} \quad (2.14 -a)$$

In end milling , as most of the cuuting is done by the fluted cutting edges on the periphery , and the surface finish acheived on the sides, is inferior to the surface finish acheived on the bottom surface for the given feed , hence equation (2.13) is used as constraint in end - milling as well.

In face milling ,the surface finish obtained using a cutter of corner angle ' C_o ' and face clearance angle ' C_e ' is given by [16],

$$h = \frac{f}{Z (\tan C_o + \cot C_e)} \quad (2.15 -a)$$

if h is the maximum permissible value of peak to valley height ,then

$$h \leq h_{max}$$

or

$$\frac{h}{h_{max}} \leq 1$$

or

$$\frac{f}{Z (\tan C_o + \cot C_e) h_{max}} \leq 1 \quad (2.15)$$

In this case , the constants in the genealized form (2.14) will be

$$a_1 = 1$$

$$b_1 = 0$$

$$C_{11} = \frac{1}{Z (\tan C_o + \cot C_e) h_{max}}$$

2. Power

As said earlier, an attempt has been made to derive the equations for maximum power utilized in various milling operations viz. peripheral, face and end, from metal cutting analysis in polynomial form. Details are presented in Appendix (B).

The total power utilized at any instant can be expressed as

$$P_c = C_2 f^{a_2} v^{b_2} \quad (2.16-a)$$

where, C_2 , a_2 and b_2 are the constants.

If P_{\max} is the maximum power available, then

$$\begin{aligned} P_c &\leq P_{\max} \\ \frac{P_c}{P_{\max}} &\leq 1 \end{aligned}$$

or

$$\frac{C_2 f^{a_2} v^{b_2}}{P_{\max}} \leq 1$$

or

$$C_{21} f^{a_2} v^{b_2} \leq 1 \quad (2.16)$$

where

$$C_{21} = \frac{C_2}{P_{\max}}$$

3. Feed per Tooth

It is constrained by the surface finish required and the power available on the machine tool. It also depends upon work material and the cutter material. The constraint can be described as

$$0 \leq f_t \leq f_{t_{\max}}$$

The value of f_{tmax} is usually either adopted from a Handbook or Shop floor data. As its value rarely exceeds 0.5 mm/tooth hence in our problem, we are taking 0.5 mm/tooth as the upper limit of the feed per tooth i.e. $f_{tmax} = 0.5$ mm/tooth.

4. Velocity

The maximum velocity is not only constrained by Power available on the machine tool but it also depends upon the cutter material and type of cut. The following values have been used as the upper limit for various cutters. The values have been compiled using (WIDIA Catalogue, WIDIA MILLING CUTTERS AND INSERTS) [17], for Carbide Cutters, and from Juneja [18] for HSS cutters in Table I.

Table I: Upper limit of cutting velocity in m/min., for various work materials.

Material	Carbides		H.S.S.	
	Roughing	Finishing	Roughing	Finishing
Cast Iron	140	160	20	40
Steel	160	180	25	40
Alloy Steel	120	160	15	20
Aluminum Alloy	700	900	200	250

While optimizing, constraints due to surface finish and power are considered as main constraints. The optimal machining parameters obtained are checked for constraints because of feed per tooth and velocity.

2.3 DATABASE DESCRIPTION

The structure and description of various databases used in this system is discussed in the following sub-sections.

1. Work Material Database

The work material Database (WP_MAT.DBF) has fields like material code, main category, material name, hardness (BHN), ultimate tensile strength (kg_f/mm^2), percent elongation, and specific cutting energy ($\text{HP} - \text{min}/\text{in.}^3$).

Material code is for identification. Main category contains information regarding major class of materials, i.e. for steel C-40, Main Category is Steel.

The values of hardness, ultimate tensile strength, percent elongation and specific cutting energy have been compiled using ref. [19], [20], [21], and [22]. The values of specific cutting energy are for chip thickness 0.25 mm and effective rake angle of zero degrees.

2. Machine Tool Database (MC-TOOL.DBF)

This database has attributes like machine tool name, operations which can be performed cutter change time (min), set-up time (min.), rapid reverse rate (m/min), Power (hp), speed steps available, upper limit (rpm), lower limit (rpm) and machining cost (Rs./min). Though cutter change time, and setup time depend on the type of cutter and operation to be done here they are considered to be constant for a particular machine tool.

The data have been compiled using references [23] and [24].

3. Cutter Database (CUTTERSPE.DBF)

This database has considerable number of fields. Among them are type of cutter, cutter material, Diameter (mm), number of teeth, width of cutter (mm), radial rake angle (deg.), clearance angle (deg.), helix angle (deg.) corner angle (deg.), purchase cost (Rs./cutter), grinding cost (Rs./min.). Grinding wheel cost (Rs./cutter), insert Cost (Rs./insert), sharpening time (min.), Tool life constants for Taylors equation, number of times the cutter can be resharpened before being discarded, and number of times the insert can be used before being discarded.

The database has been compiled using data from references [18], [24], [25] and manufacturers catalogue.

CHAPTER 3

SYSTEM IMPLEMENTATION

The system has been implemented on IBM compatible PC-XT/AT in Pascal language, using dBase III Plus as a database management system. The complete software contains various application program, datafiles, and updating programs. The main features of dBase III Plus have been described in Appendix (C) and the users manual is provided in Appendix (D).

The system flow chart shown in Fig. 4 is used for implementation and the subsequent discussions. The programs and procedures, which are called in the main program and the others in some subroutines have been discussed in the following sections.

3.1 INPUTS

(1) Input of Operations (MAIN.PRG)

As discussed earlier, the input to the system is provided in two phases. In phase I, the first input entered is the list of operations to be performed. To facilitate the listing, this program allows the user to enter the operations through menus. The complete menu structure and the various options associated with them is shown in Fig. 5. the options entered in the previous menus appears in a window at right hand corner of the screen. The "change to previous menu" option allows the user to edit the options entered in the previous menus. As shown in Fig. 5, the

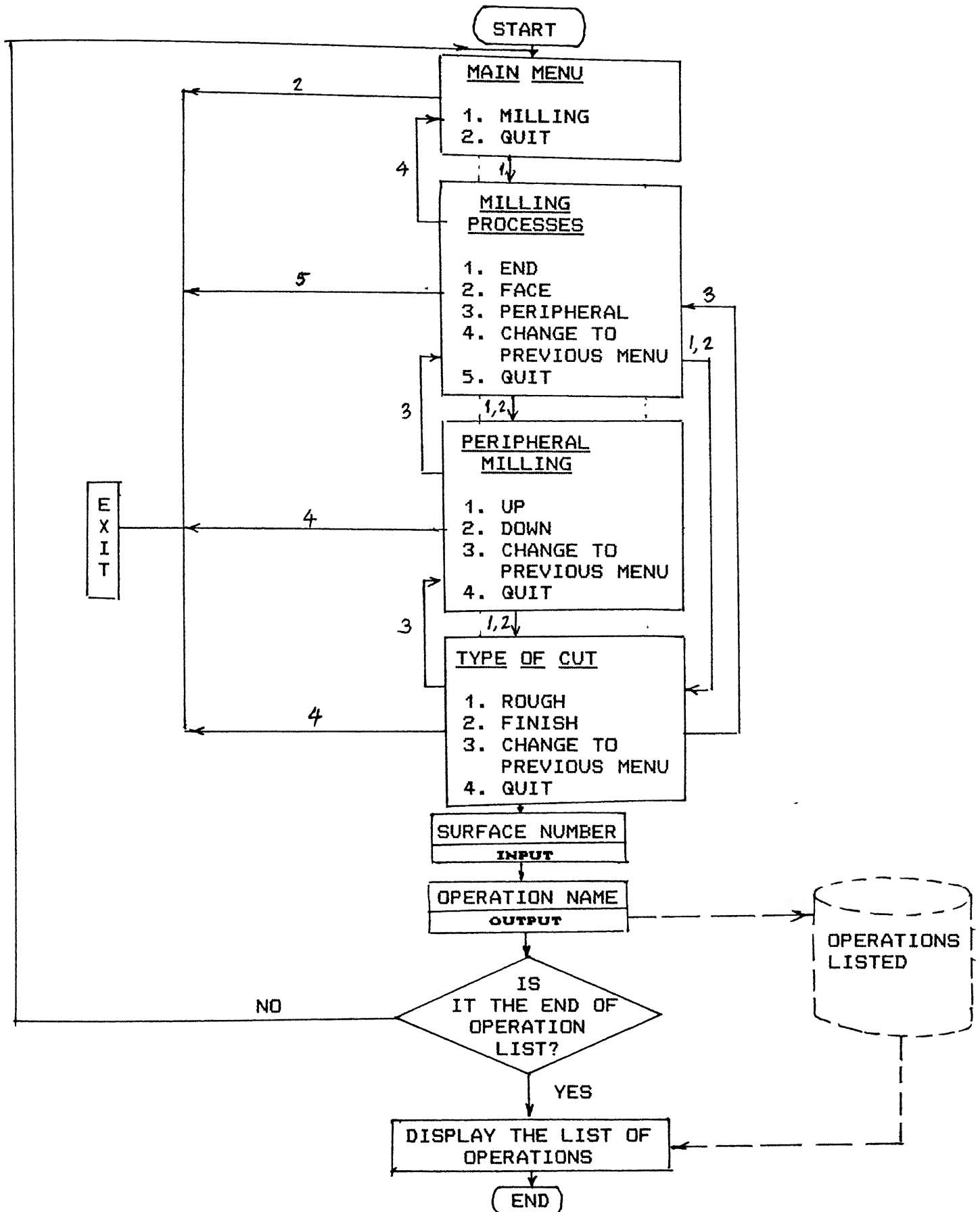


Fig. 5:00 Menu structure for listing of operations.

operations listed are stored in a temporary file. When the listing is over, the list of operations entered is displayed.

(2) Precedence Relation Among the Operations (PRED.EXE)

This procedure assists the user in entering the precedence relations. The user has to enter 'y' (yes) if the operation on the screen has any predecessor(s). the operations listed appear on the screen and the user enters the number of the operation preceding the operation under consideration. This is to be repeated if there are more predecessors for this operation.

These steps are repeated for all the operations listed.

(3) Validation of the data, regarding the precedence relations, entered by the user (Procedure VALIDATE)

This procedure is called in PRED.EXE and it checks whether the data entered by the user regarding the precedence relations is logical or not. If it is not, the error message is displayed on the screen and the user is asked to enter the precedence relations again. If the data entered is logical, then the system proceeds for the next step.

(4) Inputs for the Work Material, Objective Function for Optimization and Lot Size (WP-MENU.PRG)

This program displays the major materials which are there in the work material database. Depending upon the major material selected, a detailed list of materials of that category is displayed and the user gives option number of the work material. The specifications of the work material entered is then retrieved

from the work material database and is stored in another temporary file as shown in Fig. (1). the objective function is selected as one out of the two (minimize cost per piece, maximize production rate) and the lot size is entered upon receiving the prompt. The data entered are stored in a separate temporary file.

(5) Input for Worksurface Description (INTERACT.PRG)

The program asks the user to enter surface finish required, width and length of the surface and the depth of cut.

3.2 PROCESSING AND OUTPUTS

(6) Selection of Machine Tool (MCTOOL.PRG)

For any given operation, this program gives the list of machine tools capable of performing the operation. The user then provided with the options, selects the most suitable machine tool. The data of the machine tool selected by the user is stored in another temporary file.

(7) Processing the Data Entered (PROC.EXE)

This is the main program for processing the data entered. All the temporary files created in the above steps are read into this program (Fig. 3). Various programs which are called in this program are as follows.

(a) Determination of Optimal Condition (Procedure CALCUOPT)

This procedure apart from determining the optimal cutting conditions using the geometric programming technique, also

ROUTE SHEET & OPERATING PARAMETERS

WORK MATERIAL STEEL - STEEL C40
 OBJECTIVE FUNCTION MINIMIZE COST PER PIECE
 LOT SIZE 200

MACHINING PARAMETERS AND COSTS												
Opn No	Cutter Code	M/C Tool Code	Passes	Depth cut (mm)	OPTIMUM			Mach cost	COSTS(RUPEES)			TOTAL COST Rs/PC/opr
					Vel (m/min)	Feed. (mm/rev)	N (rpm)		Rapid trav. cost	set up cost	other cost	

FORMAT OF THE OUTPUT
 FIG 6

determine various costs and production rate. For power constraint in polynomial form, it calls procedure FORCE-PERI if the operation is peripheral milling, procedure FORCE-FACE if the operation is face milling and procedure FORCE-END if the operation is end milling.

(b) Storing the Output (procedure OUTPUT)

This procedure stores all the parameters calculated corresponding to each operations.

Steps (5), (6) and (7) are repeated for all the operations listed in Step 1.

(8) Printing of the Process Plan(PLANOUT.EXE)

This procedure prints the final output, with all the operations divided into different groups depending upon the precedence relations. For each group, its predecessor group is given. This facilitates the planner to derive different routes of doing the job. The values of optimal cutting conditions, various costs and production rate are also given. The format of the output is shown in Fig. (6).

3.3 DATABASE OPERATIONS

(9) Updating the Databases (NEW.PRG)

This programs displays the menu having various options for Appending, Editing or deleting records in the database. After entering whether to append or delete or edit, the database to be

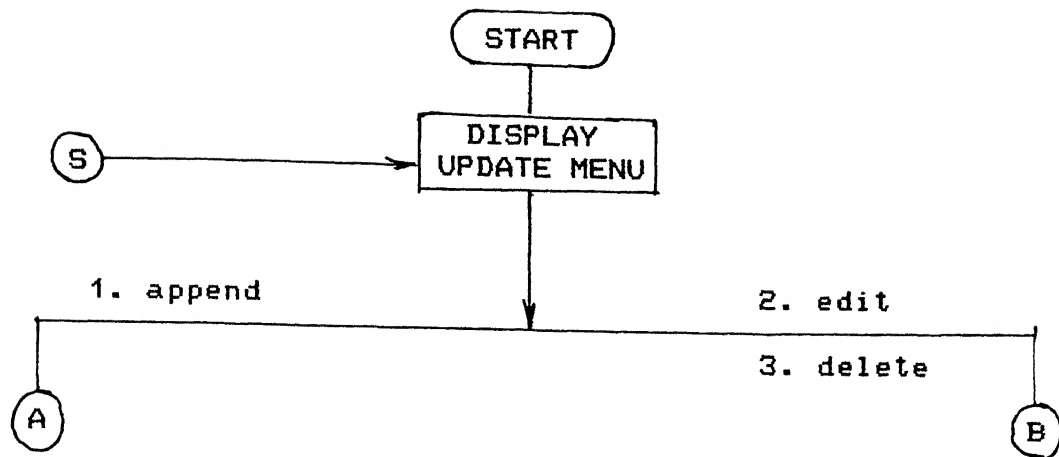


Fig. 7(a): Flow chart for updating database records.

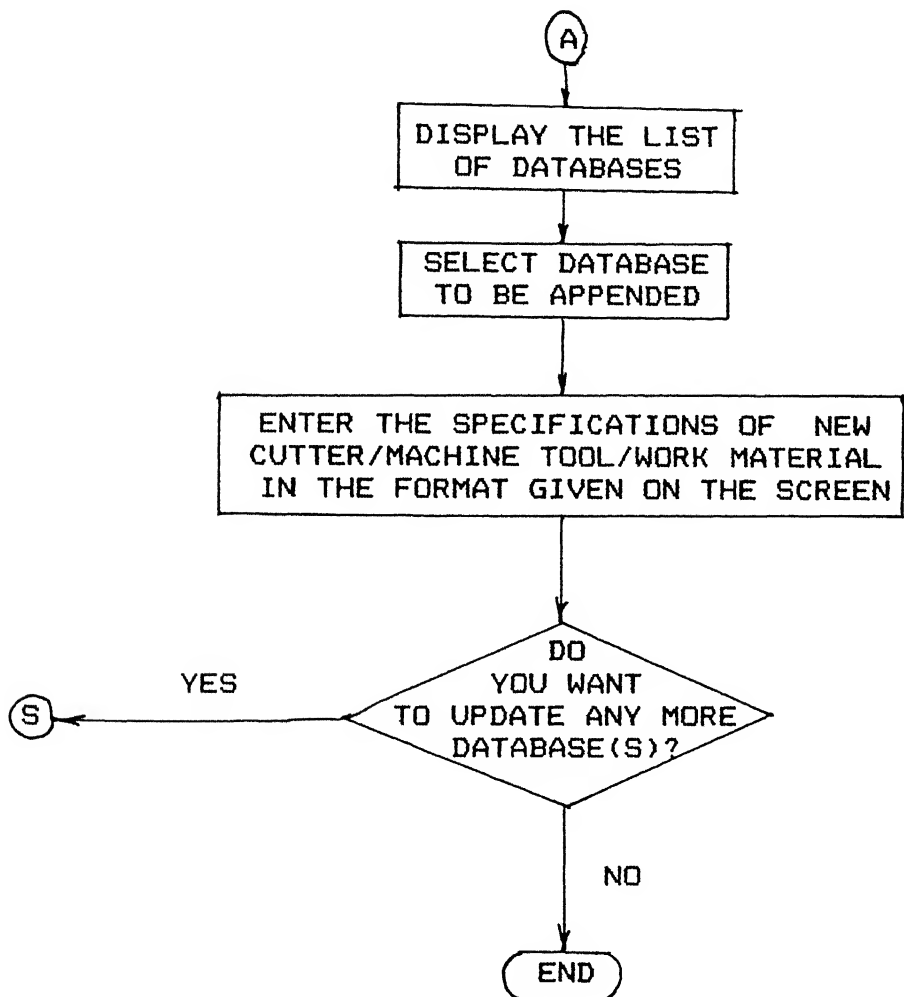


Fig. 7(b): Flow chart for appending records to database.

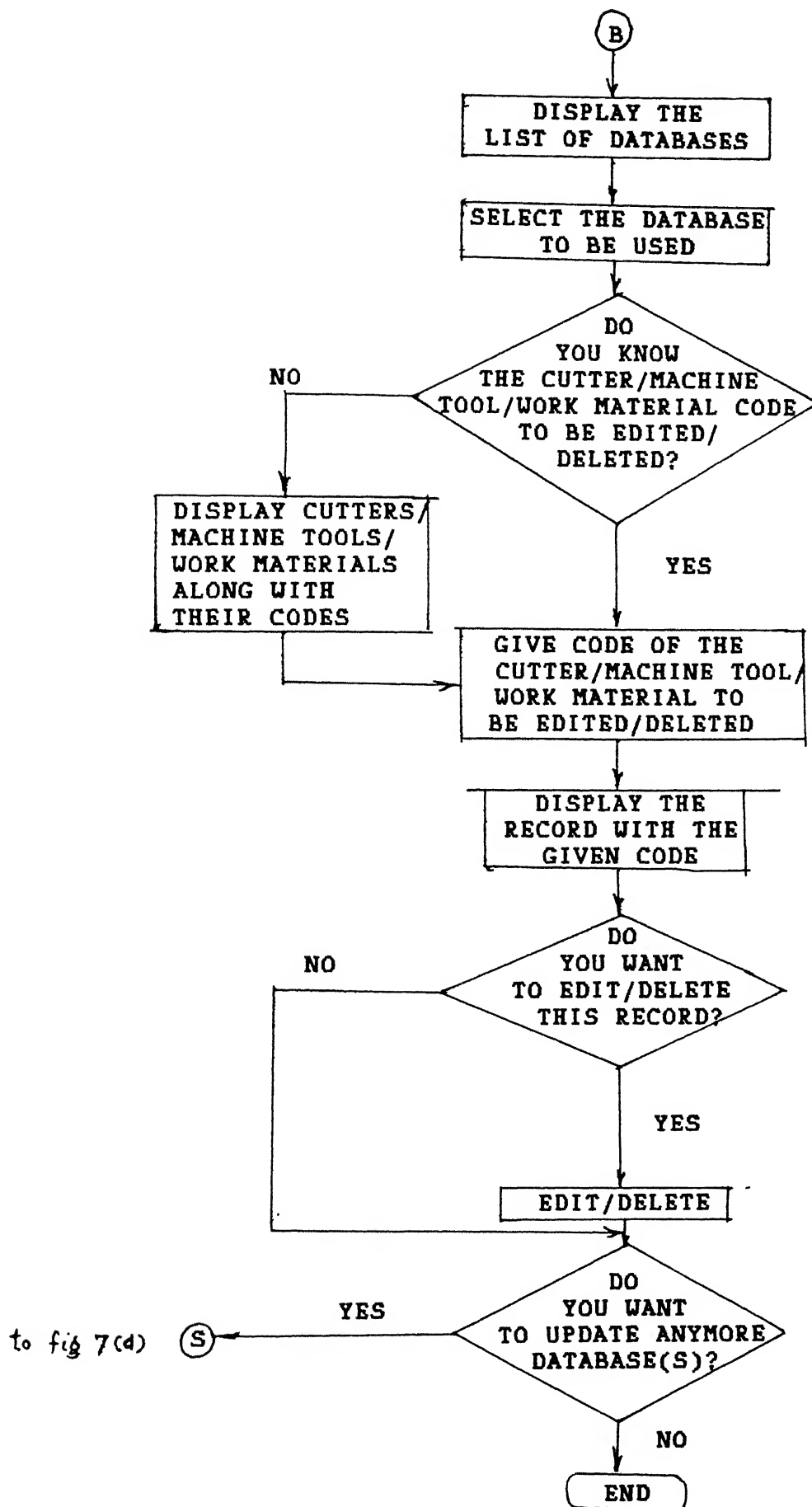


Fig. 7(c): Flow chart for editing/deleting database records.

used is entered. For appending record (Fig. 7.b) in any of the databases, the specifications are to be entered in a particular format which appears on the screen.

For editing or deleting, cutter code for cutter database, material code for material database, and machine code for machine tool database is to be entered (Fig. 7-C). If the code is not known, then, there is provision of knowing the code by selecting the appropriate option. Only permanent Databases i.e. cutter database, work material database and the machine tool database are updated.

FINITE SHEET METAL FABRICATION PARAMETERS

WORK MATERIAL STEEL - STEEL 1.411
 DELETIVE FUNCTION MINIMISE CUT REF FICLE
 UNIT SIZE 2mm

MACHINING PARAMETERS AND COSTS												
Opn No	Cutter Code	M/L Tool Code	Feed Rate	Depth cut (mm)	Vel (m/min)	OPTIMUM Feed (mm/rev)	N (rpm)	Mach Cost	CO-TE-RUPEES, Rapid 1.25 cut	set up cost	other cost	TOTAL COST Rs/PC up
GROUP 1												
PREDECESSOR GROUP : NONE												
2	FH1102	222001	1	5.00	15.394	6.000	49	2.50	0.07	0.03	0.00	2.60
GROUP 2												
PREDECESSOR GROUP : NONE												
4	FH0201	222001	2	5.00	23.625	8.000	47	4.51	0.17	0.03	0.00	4.71
5	FH0201	222001	2	5.00	23.625	8.000	47	4.51	0.17	0.03	0.00	4.71
6	FC0102	222001	3	5.00	33.929	5.000	135	3.41	0.23	0.03	0.00	3.67
7	FC0102	222001	3	0.10	179.950	5.000	716	0.64	0.23	0.03	0.01	0.91
GROUP 3												
PREDECESSOR GROUP : NONE												
8	PC1101	221001	3	10.00	159.907	10.000	509	0.50	0.25	0.03	0.01	0.78
9	PC1101	221001	1	20.00	159.907	10.000	509	0.18	0.09	0.03	0.01	0.30
GROUP 4												
PREDECESSOR GROUP : 2												
1	EC0201	222001	2	5.00	135.616	2.000	2698	0.20	0.11	0.03	0.00	0.34
GROUP 5												
PREDECESSOR GROUP : 2												
3	EH1001	222001	2	20.00	24.995	2.000	663	1.09	0.14	0.03	0.00	1.26
TOTAL PRODUCTION RATE IN PIECES PER HOUR 16.750												
TOTAL COST PER PIECE IN RUPEES 19.280												

FIG.9

CHAPTER IV

TEST RUNS AND ANALYSIS

To test the system developed, one example is taken and the output is analyzed. The details of the example are discussed in the following paragraphs.

It is considered that a semifinished block (300 mm x 100 mm x 70 mm) is provided and it is to be machined to get the final shape as shown in Fig. 8.

Apart from the design specifications as shown in Fig. (8), the following inputs are also entered as per the systems requirement.

(a) List of Operations to be performed:

The list of operations as follows, is entered.

1. ROUGHING END MILLING SL-1
2. ROUGHING FACE MILLING S2
3. ROUGHING END MILLING SL-2
4. ROUGHING FACE MILLING S5-1
5. ROUGHING FACE MILLING S5-2
6. ROUGHING FACE MILLING S4-1
7. FINISHING FACE MILLING S4-2
8. ROUGHING UP PERIPHERAL MILLING S6
9. ROUGHING UP PERIPHERAL MILLING S7

TABLE 4.2
A PORTION OF THE CUTTER DATABASE

Record#	milltype	cutmtrl	diammm	Z= no	cuttercode	alpha=rad	clearance	helix=	cutwidth
1	PERI	HSS	130.00	20	PH5201	7	10	0	14.00
2	PERI	HSS	160.00	20	PH5202	12	16	0	14.00
3	PERI	HSS	160.00	20	PH5203	4	5	0	14.00
4	PERI	HSS	160.00	20	PH5204	3	12	0	14.00
5	PERI	HSS	160.00	16	PH5205	8	25	0	12.00
6	PERI	HSS	160.00	16	PH5206	14	30	0	12.00
7	PERI	HSS	80.00	12	PH0101	7	10	0	10.00
8	PERI	HSS	80.00	12	PH0102	12	16	0	10.00
9	PERI	HSS	80.00	12	PH0103	4	5	0	10.00
10	PERI	HSS	80.00	12	PH0104	3	12	0	10.00
11	PERI	HSS	80.00	12	PH0105	8	25	0	10.00
12	PERI	HSS	80.00	10	PH0106	4	30	0	12.00
13	PERI	HSS	63.00	10	PH0107	8	12	0	12.00
14	PERI	HSS	125.00	16	PH0101	7	10	0	12.00
15	FACE	HSS	160.00	16	PH0201	7	10	20	50.00
16	FACE	HSS	160.00	20	PH0202	4	5	20	25.00
17	FACE	HSS	160.00	16	PH0203	8	25	35	20.00
18	FACE	HSS	80.00	12	PH0101	7	10	20	20.00
19	FACE	HSS	63.00	16	PH0102	4	5	20	20.00
20	FACE	HSS	100.00	12	PH1101	8	25	35	20.00
21	FACE	HSS	100.00	12	PH1102	7	10	20	20.00
22	FACE	HSS	80.00	10	PH0103	4	5	20	25.00
23	FACE	HSS	80.00	10	PH0104	8	25	35	25.00
24	END	HSS	10.00	4	EH1101	8	20	25	0.00
25	END	HSS	16.00	4	EH0201	8	20	25	0.00
26	END	HSS	25.00	4	EH0301	3	20	25	0.00
27	END	HSS	10.00	4	EH1102	4	6	15	0.00
28	END	HSS	16.00	4	EH0202	4	6	15	0.00
29	END	HSS	25.00	4	EH0302	4	6	15	0.00
30	END	HSS	12.00	4	EH1001	7	8	15	0.00
31	END	HSS	20.00	4	EH2201	7	8	15	0.00
32	END	HSS	16.00	4	EH0203	7	8	15	0.00
33	PERI	CARBIDE	80.00	14	FC0101	4	5	35	10.00
34	PERI	CARBIDE	100.00	20	FC1101	4	5	35	10.00
35	FACE	CARBIDE	80.00	10	FC0102	4	5	35	20.00
36	FACE	CARBIDE	100.00	20	FC1101	0	5	35	25.00
37	END	CARBIDE	16.00	4	EC0201	4	5	25	0.00
38	END	CARBIDE	12.00	4	EC1001	0	3	25	0.00

SL-1 and SL-2 e represents slots. As two roughing cuts are required to remove 10 mm of material on S5. Hence the two roughing cuts are listed separately as roughing face milling S5-1 and roughing for milling S5-2.

(b) Precedence Relations Among the Operations Listed

The following precedence relations are entered:

predecessor for operation 1 : 7.
predecessor for operation 2 : -
predecessor for operation 3 : 7
predecessor for operation 4 : -
predecessor for operation 5 : 4
predecessor for operation 6 : 5
predecessor for operation 7 : 6
predecessor for operation 8 : -
predecessor for operation 9 : 8

(c) Work material : Steel C-40

(d) Objective function : Minimize cost per piece

(e) Lot size : 200

(f) Vertical Machining Centre is selected for face milling and end milling operations, while horizontal machining centre for peripheral milling operations.

(g) The peak to valley values entered for roughing operations is 0.100 mm and for finishing operations 0.001.

The process plan obtained is given in Fig. 9. In the following paragraphs, the selection procedure of the cutter, using the rules described in Sec. 2.2.1, for some of the operations is discussed.

For understanding the selection procedure of the face mills, let us consider operation 4 i.e. roughing face milling S5-1, the cutter which are under consideration after each step of selection procedure is given in Table 4.1. The cutter codes have been used for convenience in the table.

The carbide cutters and the HSS cutters are considered separately, the selection procedure, however, is the same for both.

Table 4.1: Cutters under Consideration
(Roughing Face Milling S5-1)

Cutter matl.	Step 1	Step 2	Step 3		Step 4	
			Lip Angle	Under Conside- ration	Cost [*]	Recommended
H.S.S.	FH0201	FH0201	73°	FH0201	4.688	
	FH0202	FH0202	81°			
	FH0203	FH0203	57°			
	FH0101	FH0101	73°	FH0101	4.880	FH0201
	FH0102	FH0102	81°			
	FH1101	FH0103	57°			
	FH1102	FH1102	73°	FH1102	5.253	
	FH1103	FH1103	81°			
	FH0104	FH0104	57°			
CARBIDE	FC0102	FC0102	81°	FC0102	5.346	
	FC1101	FC1101	87°			

* Cost (in Rs.) involved in using a particular cutter for the operation 4.

The selection proceeds as follows:

- Step 1: All the face cutters present in the database get included into consideration.
- Step 2: As the hardness of the work material (Steel C-40) is 217 BHN, hence no cutter is discarded in this step.
- Step 3: As the ultimate tensile strength of the work material (Steel C-40) is $67 \text{ Kg}_f/\text{mm}^2$, hence the rules applied are as for Category II. The lip angles of the cutters under consideration are given in the table. On the basis of lip angles, there are three types of cutters (with angles 73° , 81° and 57°). As for Category II, cutters with intermediate lip angles are recommended, hence cutters with lip angle 73° are only considered. As the helix angle of all the cutters with lip angle 73° is same i.e. 20° (See table 4.2), hence no cutter is rejected on the basis of helix angle.
- Step 4: The cost associated with each cutter to perform the operation is calculated as shown in Table 4.1. The FH0201 cutter yields the least cost and hence is recommended for operation 4.

For understanding the selection procedure of the peripheral mills, let us consider operation 8 i.e. roughing up peripheral milling S6. The status of the cutters under consideration after each step of selection procedure is given in Table 4.3.

Table 4.3: Cutters under Consideration
(Roughing Up Peripheral Milling S6)

Cutter matl.	Step 1	Step 2	Step 3		Step 4			
			Lip Angle	Under Con.	Rad Rake	Under Com.	Cost [*]	Reco
HSS	PH5201	PH5201	73°	PH5201	7°	PH5201	3.92	
	PH5202	PH5202	62°	PH5202	12°			
	PH5203	PH5203	81°					
	PH5204	PH5204	70°	PH5204	8°			
	PH5205	PH5205	57°	PH5205	8°			
	PH5206	PH5206	46°					
	PH0101	PH0101	73°	PH0101	7°	PH0101	4.392	
	PH0102	PH0102	62°	PH0102	12°			
	PH0103	PH0103	81°					
	PH0104	PH0104	70°	PH0104	8°			
	PH0105	PH0105	57°	PH0105	8°			
	PH0106	PH0106	46°					
	PH0107	PH0107	70°	PH0107	8°			
	PH1001	PH1001	73°	PH1001	7°	PH1001	3.596	
CARB.	PC0101	PC0101	81°	PC0101	4°	PC0101	0.829	
	PC1101	PC1101	81°	PC1101	4°	PC1101	0.782	PC1101

* Cost (in Rs.) involved in using a particular cutter for the operation 8.

The selection in this case proceeds as follows:

Step 1: All the peripheral mills present in the database are considered.

Step 2: As the hardness of the work material (Steel C-40) is 217 BHN, hence no cutter is discarded in this step.

Step 3: As the ultimate strength of the work material (Steel C-40) is $67 \text{ kg}_f/\text{mm}^2$, hence the rules applied are as for

Category II. the lip angles of the cutters under consideration are also given in Table 4.3. On the basis of lip angle criterion, the cutters with highest and lowest lip angles i.e. with 81° and 46° are not considered. On the basis of radial rake angle criterion, the cutters with radial rake angle 7° qualifies.

Step 4: The cost criterion is used for the final recommendation of a cutter for this operation. The cost associated with each cutter to carry out this operation is also shown. As the cost associated with PC1101 is the least, PC1101 is recommended.

Table 4.4: Cutters under Consideration
(Roughing End Milling SL-1)

Cutter matl.	Step 1	Step 2	Step 3		Step 4	
			Lip Angle	Under Conside- ration	Cost [*]	Recommended
H.S.S.	EH1101	EH1101	62°			
	EH0201	EH0201	62°			
	EH0301	EH0301	62°			
	EH1102	EH1102	70°			
	EH0202	EH0202	70°			
	EH0302	EH0302	70°			
	EH1001	EH1001	75°	EH1001	0.952	
	EH2201	EH2201	75°	EH2201	0.763	
	EH0203	EH0203	75°	EH0203	1.227	
CARBIDE	EC0201	EC0201	81°	EC0201	0.339	EC0201
	EC1001	EC1001	87°			

* Cost (in Rs.) involved in using a particular cutter for the operation 1.

The operations listed are divided into different groups depending on the precedence relations entered. The operations in each group are to be performed strictly in the given sequence. For each group, the predecessor group(s) is(are) given. This facilitates the planner to derive feasible routes in which the job can be done.

The remaining details given in the process plan are self explanatory.

CHAPTER V

CONCLUSIONS

5.1 CONCLUSION

A generative process planning system is developed for milling operations. It supports the three major milling operations: end milling, face milling and peripheral milling.

The data regarding the cutters, machine tools, and work materials are stored in databases. The database management system used is dBASE III Plus.

Geometric programming technique has been used to determine the optimal cutting conditions, as it is very useful when the objective function is of more than second degree, and the constraints are nonlinear.

The use of power equations derived from the metal cutting analysis has made this system more versatile as there is no restriction as regards the power equations. The use of empirical relations, requires the data regarding the exponents to be stored in the database.

The selection of cutters is done automatically. Some rules have been made for selecting the cutters. All the aspects have not been taken into consideration in the rules hence the rules cannot be considered to be universal. The rules need more refinement.

The output contains details regarding the various costs from which one gets a very clear picture of contribution of actual machining cost to the total machining cost. From the output one can very easily determine various routings for doing the same job.

5.2 SCOPE FOR FUTURE STUDY

In the system, the information for sequencing (i.e. the precedence relations) is provided by the user. Efforts should be made to extract features from CAD model and decide upon the operations which should be performed. Further, it can be extended to give the sequence of operations.

As regards the major milling operations, they are taken care of by this system. The system would become more useful if other milling operations like T slot cutting, dove tail milling etc. are also included. The system has a facility of using empirical relations for power but an attempt should be made to go for the metal cutting analysis of other milling operation as well.

It has been assumed in this system that all the machine tools and the cutters are available for process planning of each new part. The system could be made more practical if, the status of the cutters and machine tools availability is also incorporated.

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APPENDIX A

GENERALIZED OPTIMIZATION MODEL

A generalized optimization model for determining the optimal feed and velocity can be expressed as:

Find,

$$X = \begin{bmatrix} f \\ v \end{bmatrix}$$

Minimize

$$f(X) = C_{01} f^{a0} v^{b0} + C_{02} f^{c0} v^{d0}$$

subject to

$$C_{11} f^{a1} v^{b1} \leq 1;$$

and $C_{21} f^{a2} v^{b2} \leq 1.$

SOLUTION METHODOLOGY

Step 1: Replace given problem by an equivalent dual problem.

For above problem, the dual problem would be,

Find,

$$X = \begin{bmatrix} \lambda_{01} \\ \lambda_{02} \end{bmatrix}$$

Maximize

$$v(\lambda) = \left(\frac{C_{01}}{\lambda_{01}} \right)^{\lambda_{01}} \left(\frac{C_{02}}{\lambda_{02}} \right)^{\lambda_{02}} (C_{11})^{\lambda_{11}} (C_{21})^{\lambda_{21}}$$

subject to,

$$\lambda_{01} + \lambda_{02} = 1; \quad \text{Normality constraint}$$

$$a_0 \lambda_{01} + c_0 \lambda_{02} + a_1 \lambda_{11} + a_2 \lambda_{21} = 0 \quad \text{Orthogonal}$$

$$b_0 \lambda_{01} + d_0 \lambda_{02} + b_1 \lambda_{11} + b_2 \lambda_{21} = 0 \quad \text{constraint}$$

$$\lambda_{01} \geq 0, \quad \lambda_{02} \geq 0, \quad \lambda_{11} \geq 0, \quad \lambda_{21} \geq 0,$$

Non negativity condition

where,

$$\lambda_{01} = \frac{C_{01} f^{a0} v^{b0}}{v(\lambda)} ;$$

$$\lambda_{02} = \frac{C_{02} f^{c0} v^{d0}}{v(\lambda)} ;$$

$$\lambda_{11} = C_{11} f^{a1} v^{b1} ;$$

$$\lambda_{21} = C_{21} f^{a2} v^{b2} ;$$

and are called as dual variables while $v(\lambda)$ is called as dual function.

Step 2: With the use of normality constraint and orthogonality constraint, find dual variables in terms of any one dual variable i.e. find λ_{02} , λ_{11} , λ_{21} in terms of λ_{01} .

Step 3: Substitute the values of the dual variables in the equation for dual function i.e. find dual function $v(\lambda)$ in terms of λ_{01} .

Step 4: At stationary point

$$\frac{\partial v(\lambda)}{\partial \lambda_{kj}} = 0$$

so take natural log of the expression for $v(\lambda)$ in Step 3 and differentiate it with respect to λ_{01} and equate it to zero.

From the equation which we obtain, we can find the value of λ_{01} .

Step 5: From the value of λ_{01} find the values of the remaining dual variables and the dual function.

Then using the equations,

$$\lambda_{01} = \frac{C_{01} f^{ao} v^{bo}}{v(\lambda)}$$

and,

$$\lambda_{02} = \frac{C_{02} f^{co} v^{do}}{v(\lambda)}$$

find the values of f and V .

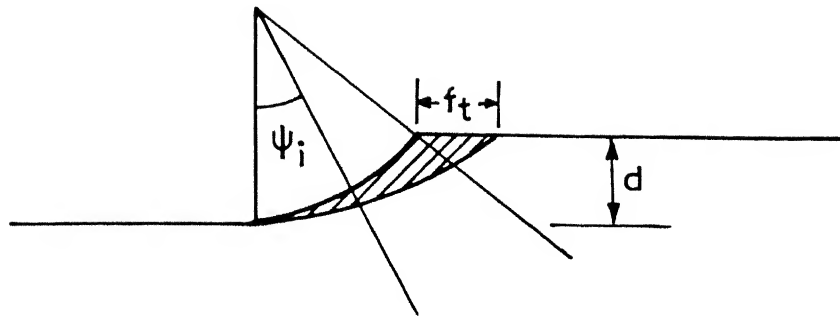


Fig. B1-a The uncut area of cross-section traversed by on tooth in plain milling operation.

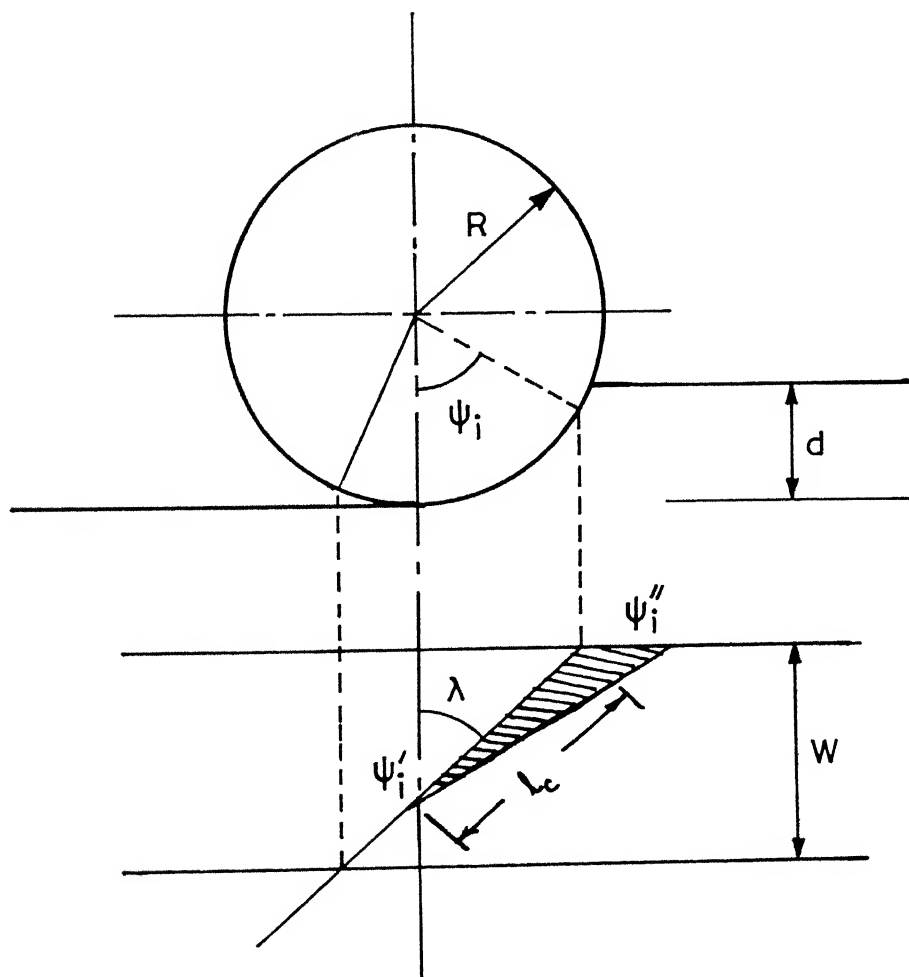


Fig. B1-b The uncut area of cross-section traversed by one tooth in helical milling operation.

APPENDIX B

POWER EQUATIONS FOR MILLING OPERATIONS

This appendix presents the expressions and their derivation for power consumption in end, face, peripheral milling.

B-1 POWER EQUATION FOR PERIPHERAL MILLING

Uncut chip area in plain milling cutter is

$$A_i = W f_t \sin \psi_i \quad (B.1)$$

(3.79 Bhattacharya [26])

where ψ_i is the instantaneous position of the cutting edge in cutting, measured from the vertical axis as shown in Fig. (B1-a).

In helical cutter,

$$A_i = \frac{D}{2} f_t \cot \lambda (\cos \psi_i' - \cos \psi_i'') \quad (B.2)$$

(3.86 - Bhattacharya [26])

ψ_i' and ψ_i'' are instantaneous entry and exit angles as shown in Fig. B1-b.

Instantaneous area of shear,

$$A_{s_i} = \frac{A_i}{\sin \phi_n} \quad (B.3)$$

where ϕ_n is the normal shear angle.

Dynamic shear stress

$$\begin{aligned} \tau_s &= 0.74 \sigma_u \epsilon^{0.6\Delta} && \text{For ductile materials (5.35 [26])} \\ \tau_s &= 0.175 \text{ BHN} && \text{For brittle materials (5.40 [26])} \end{aligned} \quad (B.4)$$

Instantaneous shear force

$$F_{s_i} = \tau_s A_{s_i} \quad (B.5)$$

and instantaneous tangential force [16]

$$F_{T_i} = F_{s_i} \left[\frac{\cos(\beta_n - \alpha_n) \cos \lambda - \sin \lambda \tan \eta_c \sin \beta_n}{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2 \eta'_c \sin^2 \beta_n} \right] \quad (B.6)$$

$$F_{T_i} = \tau_s \frac{D}{2} f_t \cot \lambda (\cos \psi'_i - \cos \psi''_i) \left[\frac{\cos(\beta_n - \alpha_n) \cos \lambda - \sin \lambda \tan \eta_c \sin \beta_n}{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2 \eta'_c \sin^2 \beta_n} \right] \quad (B.7)$$

Power being consumed at any instant,

$$P_i = F_{T_i} V \quad (B.8)$$

The total power consumed at any instant

$$P_c = \sum_1^{z_1} P_i$$

Thus at any instant during cutting the total power consumed

$$P_c = \tau_s \frac{D}{2} f_t V \sum_1^{z_1} \cot \lambda (\cos \psi'_i - \cos \psi''_i) \left[\frac{\cos(\beta_n - \alpha_n) \cos \lambda - \sin \lambda \tan \eta_c \sin \beta_n}{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2 \eta'_c \sin^2 \beta_n} \right] \quad (B.9)$$

where z_1 is the number of teeth engaged.

$$P_c = f V C_{21}$$

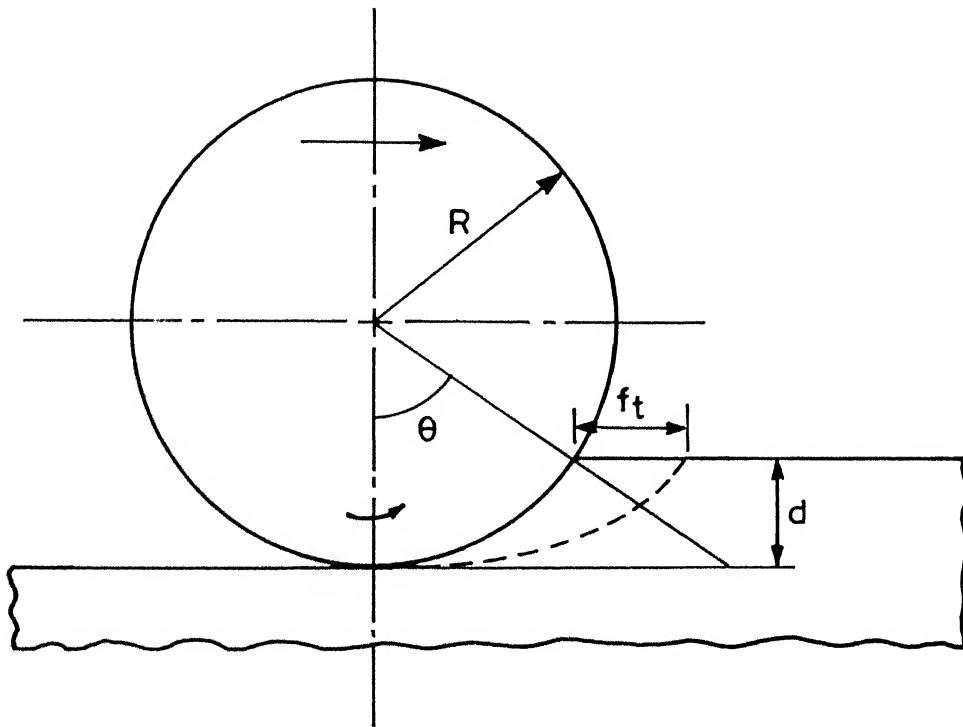


Fig. B2 The maximum chip thickness in plain milling.

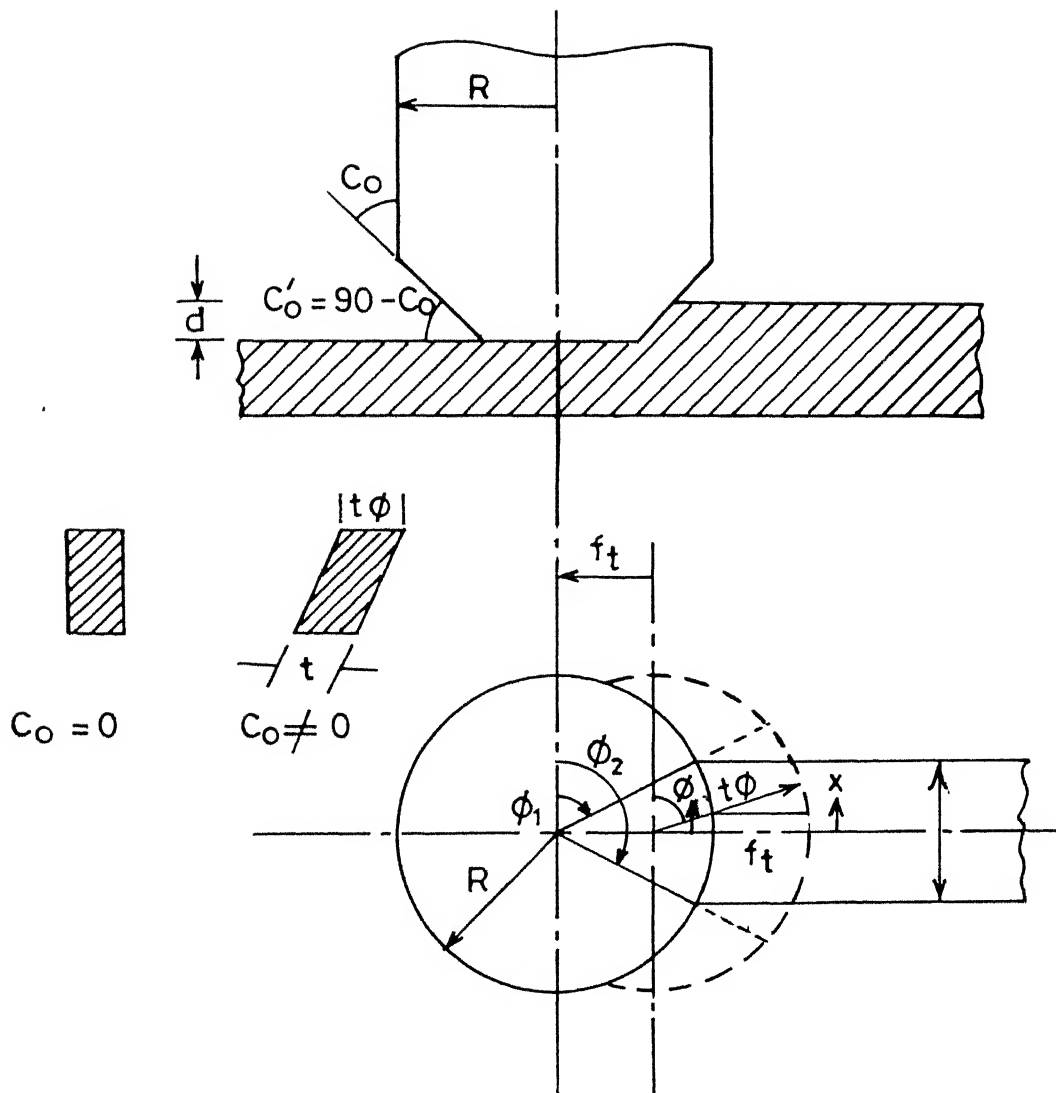


Fig. B3 The geometry of chip formation in face milling.

where,

$$C_{21} = \tau_s \frac{D}{2} \frac{1}{Z} \sum_1^{Z_1} \cot \lambda (\cos \psi_1' - \cos \psi_1'') \left[\frac{\cos (\beta_n - \alpha_n) \cos \lambda - \sin \lambda \tan \eta_c \sin \beta_n}{\cos^2 (\phi_n + \beta_n - \alpha_n) + \tan^2 \eta_c \sin^2 \beta_n} \right] \quad (B.10)$$

Thus we have got the equation for total power consumed at any instant in peripheral milling in posynomial form.

$$P_c = f V C_{21} \quad (B.11)$$

As it is clear, that any tooth encounters the maximum force during cutting when the uncut chip thickness is maximum. As shown in Fig. B2 at angle θ , the chip thickness attains the maximum value. So corresponding to angle θ , we find the tangential force on the tooth. Then we find the relative positions of other engaged teeth and accordingly calculate the cutting forces. The summation of power utilized at each tooth gives the maximum power consumption.

B-2 POWER EQUATION FOR FACE MILLING

From Fig. B3

$$\begin{aligned} t_\phi &= f_t \sin \phi, \\ t &= t_\phi \sin C_o', \\ t &= f_t \sin \phi \sin C_o' \end{aligned} \quad (B.12)$$

If d is the depth of cut then the length of chip

$$l_c = \frac{d}{\sin C_o}, \quad \frac{1}{\cos \lambda} \quad (B.13)$$

Thus the instantaneous area of uncut chip

$$\begin{aligned}
 A_i &= l_c t \\
 &= \frac{d}{\sin C_o} \cdot \frac{1}{\cos \lambda} t \\
 A_i &= \frac{f_t d \sin \phi}{\cos \lambda}
 \end{aligned} \tag{B.14}$$

The specific cutting energy K_{sp} is defined as the energy per unit volume removed [16].

$$\text{Thus, } K_{sp} = \frac{U}{V l_c t} \tag{B.15}$$

where, U is the total energy consumed/time.

$$\text{or, } K_{sp} = \frac{U}{V A_i}$$

from (B.14) the instantaneous area of uncut chip

$$A_i = \frac{f_t d \sin \phi}{\cos \lambda}$$

Thus,

$$K_{sp} = \frac{U \cos \lambda}{V f_t d \sin \phi}$$

$$U_i = \frac{K_{sp} V f_t d \sin \phi}{\cos \lambda} \tag{B.16}$$

$$U_i = F_{T_i} V$$

so,

$$F_{T_i} V = \frac{K_{sp} V f_t d \sin \phi}{\cos \lambda}$$

$$F_{T_i} = \frac{K_{sp} f_t d \sin \phi}{\cos \lambda} \tag{B.17}$$

If we go through the Eqn. (B.17), we find that it does not represent true instantaneous value of the tangential force because K_{sp} is also the function of ϕ [21].

According to Shaw [21],

- (i) K_{sp} is the function of workpiece material.
- (ii) K_{sp} is the function of effective rake angle of tool (α_e)
(it decreases about 1% per degree increase in effective rake angle).
- (iii) K_{sp} is the function of undeformed chip thickness

$$K_{sp} \sim \frac{1}{t^{0.2}} \quad (B.18)$$

If K_{sp_1} is the specific cutting energy, for uncut chip thickness t_1 and cutter rake angle α_1 , for a particular work material then, the specific cutting energy K_{sp_2} , for uncut chip thickness t_2 and cutter rake angle α_2 , can be represented by

$$K_{sp_2} = K_{sp_1} \frac{t_1^{0.2}}{t_2^{0.2}} \left(1 - \frac{\alpha_1 - \alpha_2}{100}\right); \quad (B.19)$$

Thus, if we have value of specific cutting energy, for a particular work material, at certain rake angle and for certain chip thickness, we can find the value of specific cutting energy in any other situation.

$$K_{sp} = K_{sp_1} \frac{t_1^{0.2}}{t^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right); \quad (B.20)$$

Substituting this in Eqn. (B.17)

$$\begin{aligned} F_{T_i} &= \frac{K_{sp} f_t d \sin \phi}{\cos \lambda} \\ &= K_{sp_1} \frac{t_1^{0.2}}{t^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{f_t d \sin \phi}{\cos \lambda} \end{aligned}$$

From Eqn. (B.12),

$$t = f_t \sin \phi \sin C_o'$$

therefore,

$$F_{T_i} = K_{sp1} \frac{t_1^{0.2}}{(f_t \sin \phi \sin C_o')^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{f_t d \sin \phi}{\cos \lambda}$$

$$F_{T_i} = K_{sp1} \frac{t_1^{0.2}}{(\sin C_o')^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{d}{\cos \lambda} f_t^{0.8} (\sin \phi)^{0.8}$$

$$F_{T_i} = K_{sp1} \frac{t_1^{0.2}}{(\sin C_o')^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{d}{\cos \lambda} \left(\frac{f}{Z}\right)^{0.8} (\sin \phi)^{0.8}$$

(B.21)

$$F_{T_i} = C_2' f^{0.8} \sin \phi^{0.8} \quad (B.22)$$

where,

$$C_2' = K_{sp1} \frac{t_1^{0.2}}{(\sin C_o')^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{d}{\cos \lambda} \left(\frac{1}{Z}\right)^{0.8} \quad (B.23)$$

Thus, power consumed at any instant can be given by

$$P_c = \sum_1^{z_1} F_{T_i} V$$

$$P_c = C_2' f^{0.8} V \sum_1^{z_1} \sin \phi^{0.8} \quad (B.24)$$

For calculating maximum power utilized while cutting, the logic applied is the same as discussed in Sec. (B-1). Eqn. B.24 would give maximum power consumed at any instant while cutting

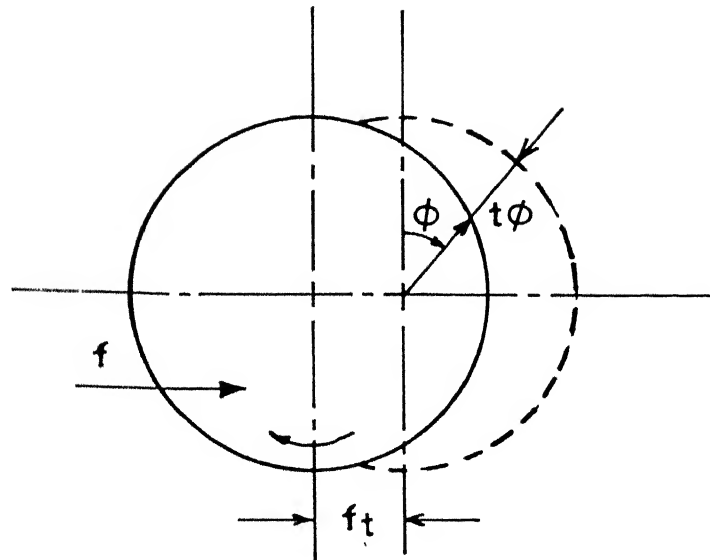
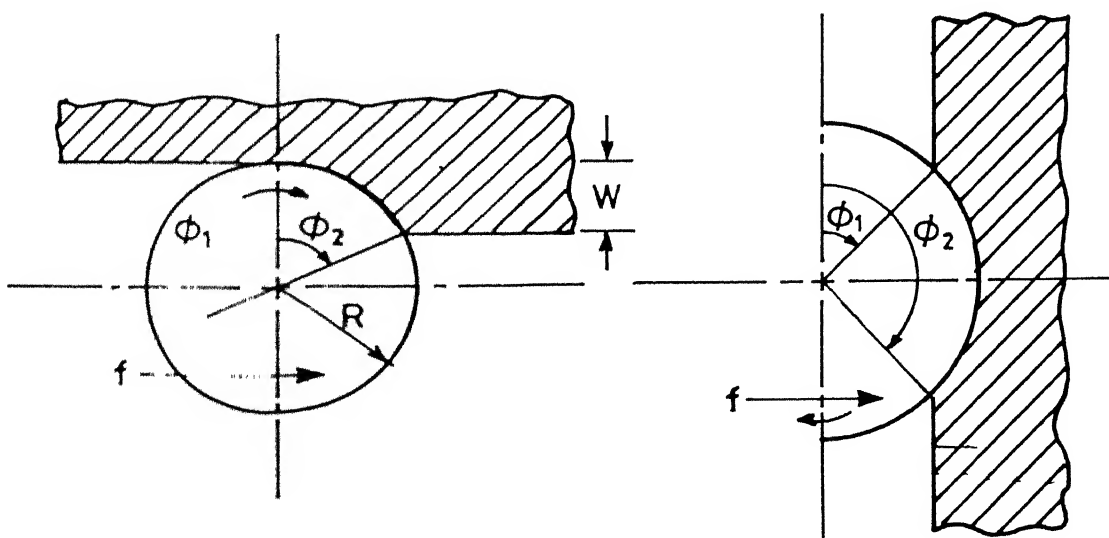


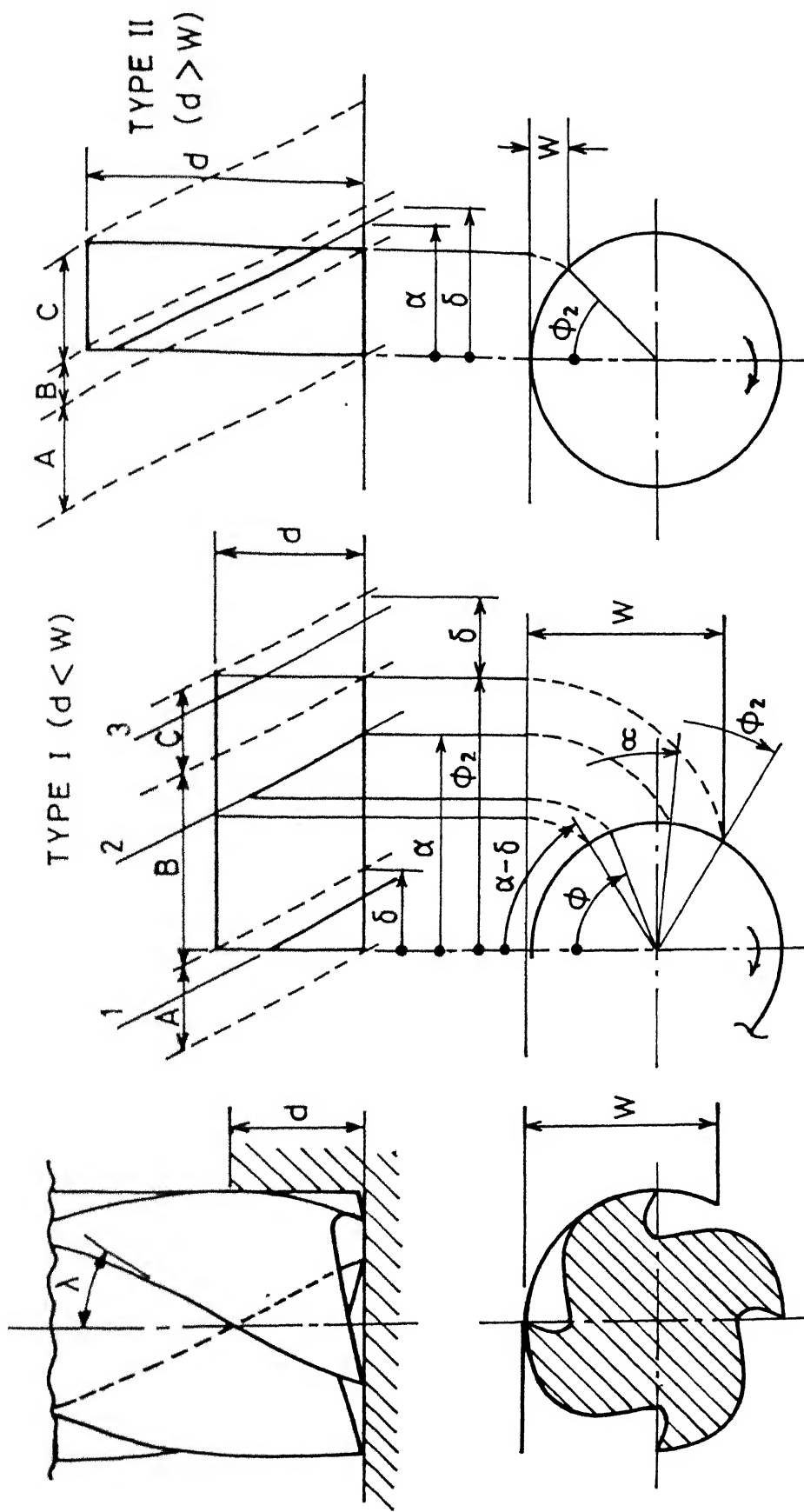
Fig. B4 The variation of chip thickness in end milling.



Steady state cutting

Unsteady state cutting

Fig. B5 The cutting action in end milling.



(a)

(b) The action of one tooth on a plan

Fig. B6 The cutting action in end milling.

when one of the engaged teeth, is at a position where chip thickness is maximum.

B-3 POWER EQUATION FOR END MILLING

In deriving the formula for power in end milling Tlusty's [27] analysis has been used. The tangential cutting force on a part of one tooth is considered. The position of any part of the cutting edge in the cut is ϕ , measured from the vertical axis. The instantaneous chip thickness

$$t = f_t \sin \phi \quad (B.25)$$

In Fig. (B6-a) right hand helix is used and the teeth which are cutting are at the back of the plan view as indicated by broken lines. In Fig. (B6-b), the action of one tooth is considered on a plan which shows the development of the surface of the cut. The cutting edge is then a straight line inclined by λ (helix) and it moves from left to right. Three successive positions of the moving edge are indicated. Any such position is indicated by the angle α (shown for position 2) through which the leading point of the cutting edge has moved from the beginning of its cutting action. In position 2, the total length of the edge engaged in the cut is

$$R \delta = d \tan \lambda \quad (B.26)$$

and the angular position ϕ of the individual points of the edge spread from $(\alpha - \delta)$ to α . The whole cutting action may be divided into three phases.

In phase A, the length of cutting edge increases from 0 to the maximum depth d (to the engagement angle δ). In phase B, the

length of cutting edge remains constant while it moves through varying chip thickness. In phase C, the cutting edge length gradually decreases and finally it becomes zero. Thus the range of the values of α is

Phase A : $[0, \delta]$

Phase B : $[\delta, \phi_2]$

Phase C : $[\phi_2, \phi_2 + \delta]$

For a large ratio of depth d to width of cut W , the cycle is slightly different. The engagement angle of the cutting edge reaches at the end of phase A a value ϕ_2 which is smaller than $\delta = (d \tan \beta)/R$ throughout phase B, the cut spreads constantly over a range of $0 < \phi < \phi_2$. The force thus remains constant in this phase. The ranges of α are now.

Phase A : $[0, \phi_2]$

Phase B : $[\phi_2, \delta]$

Phase C : $[\delta, \phi_2 + \delta]$

In any position of the cutting edge during the cut the cutting force is distributed non uniformly along the edge because its individual points have different angular position ϕ , and consequently, they cut different chip thicknesses.

We know that,

$$F_T = K_{sp} (\text{area of cut}) \quad (\text{B.27})$$

The contribution of an element dy of the cutting edge to the total cutting force is

$$dF_T = K_{sp} f_t \sin \phi dy$$

$$dF_T = K_{sp} f_t \sin \phi R d\phi / \tan \lambda \quad (\text{B.28})$$

Here, K_{sp} is the function of ϕ from (B.20),

$$\begin{aligned} K_{sp} &= K_{sp1} \frac{t_1^{0.2}}{t^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right); \\ &= K_{sp1} \frac{t_1^{0.2}}{(f_t \sin \phi)^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right); \end{aligned}$$

Thus,

$$dF_T = K_{sp1} \frac{t_1^{0.2}}{(f_t \sin \phi)^{0.2}} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{f_t R \sin \phi d\phi}{\tan \lambda}$$

$$dF_T = K_{sp1} t_1^{0.2} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{R}{\tan \lambda} f_t^{0.8} (\sin \phi)^{0.8} d\phi$$

$$dF_T = K_{sp1} t_1^{0.2} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{f^{0.8} R (\sin \phi)^{0.8} d\phi}{Z^{0.8} \tan \lambda}$$

$$dF_T = C_2' f^{0.8} (\sin \phi)^{0.8} d\phi \quad (B.29)$$

where,

$$C_2' = K_{sp1} t_1^{0.2} \left(1 - \frac{\alpha - \alpha_1}{100}\right) \frac{R}{Z^{0.8} \tan \lambda} \quad (B.30)$$

Thus,

$$dF_T = C_2' f^{0.8} (\sin \phi)^{0.8} d\phi$$

Integrating,

$$F_{Ti} = C_2' f^{0.8} \int (\sin \phi)^{0.8} d\phi \quad (B.31)$$

In Type I,

Phase A

α varies from 0 to δ , and

ϕ varies from 0 to α .

Thus,

$$F_{t_i} = C_2' f^{0.8} \int_0^{\alpha} (\sin \phi)^{0.8} d\phi \quad (B.32)$$

so, when $\alpha = 0$ to δ we use this equation to find instantaneous tangential force on one tooth.

Phase B

α varies from δ to ϕ_2 , and
 ϕ varies from $\alpha - \delta$ to α .

Thus,

$$F_{t_i} = C_2' f^{0.8} \int_{\alpha - \delta}^{\alpha} (\sin \phi)^{0.8} d\phi \quad (B.33)$$

so when α lies between δ to ϕ_2 we use this eqn.

Phase C

α varies from ϕ_2 to $\phi_2 + \delta$, and
 ϕ varies from $\alpha - \delta$ to ϕ_2 .

Thus,

$$F_{t_i} = C_2' f^{0.8} \int_{\alpha - \delta}^{\phi_2} (\sin \phi)^{0.8} d\phi \quad (B.34)$$

so when α lies between ϕ_2 to $\phi_2 + \delta$ we use this eqn.

Similarly, for Type II,

Phase A

α varies from 0 to ϕ_2 , and
 ϕ varies from 0 to α .

and
$$F_{t_i} = C_2' f^{0.8} \int_0^{\alpha} (\sin \phi)^{0.8} d\phi \quad (B.35)$$

Phase B

α varies from ϕ_2 to δ , and
 ϕ varies from 0 to ϕ_2 .

$$\text{and } F_{t_i} = C_2' f^{0.8} \int_0^{\phi_2} (\sin \phi)^{0.8} d\phi \quad (\text{B.36})$$

Phase C

α varies from δ to $\phi_2 + \delta$, and

ϕ varies from $\alpha - \delta$ to ϕ_2 .

$$\text{and } F_{t_i} = C_2' f^{0.8} \int_{\alpha-\delta}^{\phi_2} (\sin \phi)^{0.8} d\phi \quad (\text{B.37})$$

Total power consumed at any instant,

$$P_c = \sum_1^{z_1} F_{T_i} V$$

The total power consumed will be maximum if one of the engaged tooth is at position where chip thickness is maximum.

Thus the angle at which the chip thickness would be maximum is found. The relative positions of other teeth is determined accordingly. Depending upon the phase in which they lie, corresponding equations are used for finding the force on each tooth. The summation of power used at each tooth engaged would give the total maximum power consumed while cutting.

APPENDIX C

As discussed in Chapter III, the DBMS used for the system implementation is dBase III plus. The reason for using dBase III plus as DBMS are:

1. The Databases can be handled easily. Updating is simple.
2. It allows to interact with our data through menu selection which avoids the tedious job turning the pages of manuals.
3. The system developed was to be made user friendly, the application programs of dBase III plus took care of this requirement.
4. Frequent and fast searching of database is needed in the system, it is possible in the selected DBMS.

APPENDIX D

USER'S MANUAL

In run the system, the necessary instructions are given in this appendix.

The following commands are to be used for running this system. User should make sure that the hard disk has dBase III plus. The following commands are to be entered often inserting the floppy.

```
C> CD DBASE
```

```
C> DBASE
```

(after pressing return the dBase III plus dot prompt would appear).

- . Set defa to A: (this command takes you the floppy drive)
- . do main

Necessary instructions are given after this at various places accordingly the user has entered the data or information.

As the data bases are dBase III plus, hence all the facilities of dBase III plus can be used. But, for a user who is new to the dBase III plus, there is a facility of updating the database. The facilities made available are APPEND, EDIT OR DELETE records in the database. The command for this is

```
.DO NEW
```

You have to select one of the options given on the screen. Further you have to select the database which is to be updated. After updating if you want to update any other database or the same database you continue else come out.